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INVESTIGATION OF THE RELATIONS BETWEEN NEAT RESIN AND ADVANCED COMPOSITE MECHANICAL PROPERTIES

VOLUME II - APPENDICES

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Grant NAGI-277
November 1984

NASA
National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

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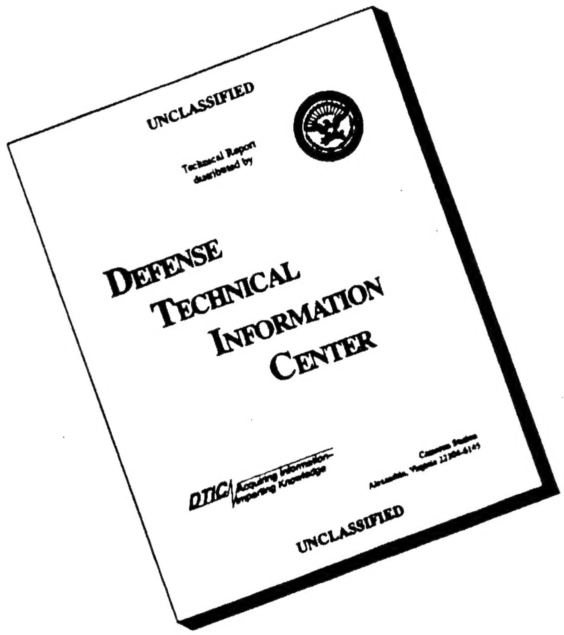

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VOLUME II - APPENDICES

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NOVEMBER 1984

TECHNICAL REPORT
NASA-LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

RESEARCH GRANT NO. NAG-1-277

COMPOSITE MATERIALS RESEARCH GROUP
MECHANICAL ENGINEERING DEPARTMENT
UNIVERSITY OF WYOMING
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PREFACE

This technical report presents the results of a one-year neat resin characterization and micromechanical prediction program sponsored by NASA-Langley Research Center, under Research Grant NAG-1-277.

All work was performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming. Co-Principal Investigators were Mr. Richard S. Zimmerman, Staff Engineer and Dr. Donald F. Adams, Professor. The analytical micromechanics studies were under the direction of Mr. David E. Walrath, Staff Engineer. Making major contributions to the program were Larry G. Adams, Beth E. Rogers, and Edward D. Schaffer, graduate students in Mechanical Engineering, and Eric Q. Lewis, Craig H. Johnson, Jeffrey A. Kessler, Thomas A. Ohnstad, Mark Vanderbleek, and Donald B. Hardy, undergraduate students in Mechanical Engineering, and all members of the Composite Materials Research Group. Substantial help in casting neat resin specimens was provided by Mr. Edwin M. Odom, Staff Engineer.

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VOLUME II

APPENDIX A

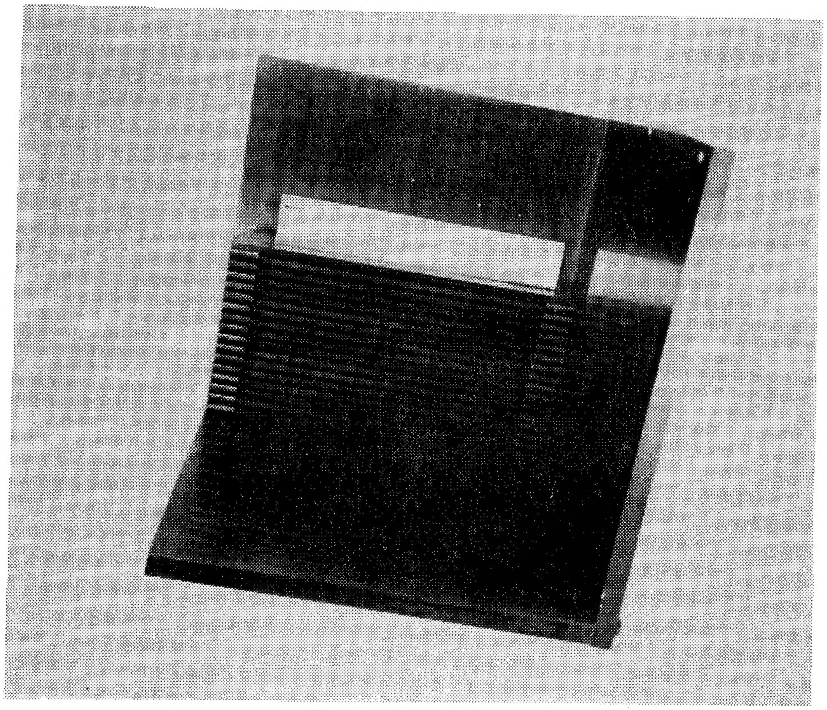
NEAT RESIN CASTING TECHNIQUES

A.1 Introduction

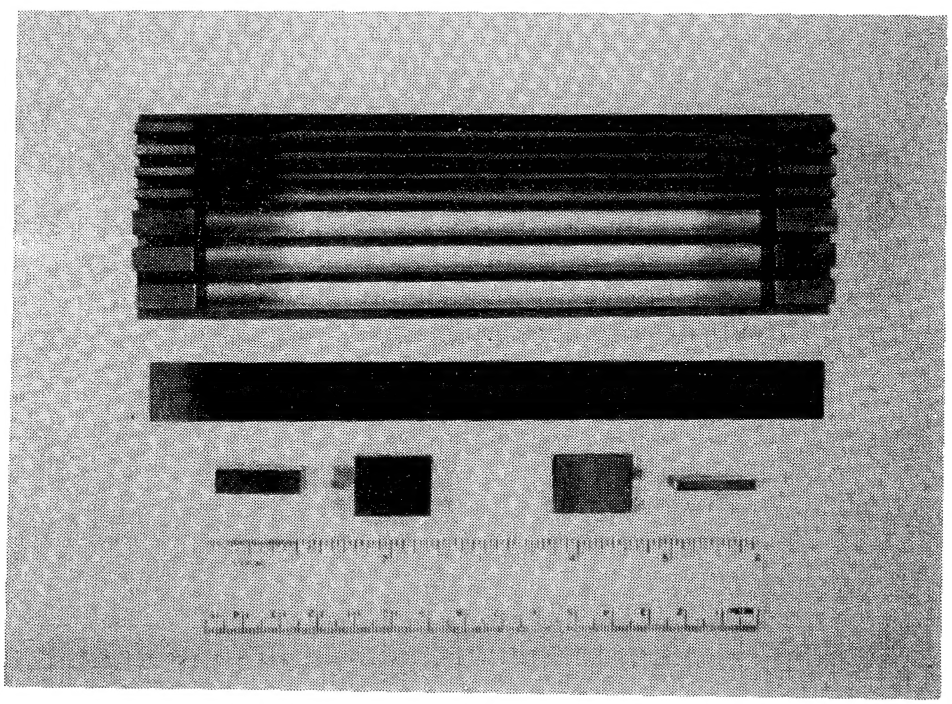
The Composite Materials Research Group has been very active in the development of methods to cast thermoset resins into the necessary shapes for mechanical and physical testing. This fabrication of neat resins has evolved over the last 5-6 years into a fairly routine process. Nine resin systems from several resin formulators have been molded including Hercules 3501-6, 3502, 2220-1, 2220-3, and 4001, Shell Epon 9101, Ciba-Geigy Fibredux 914 and Fiberite 930 and 934. Various specimen configurations were needed for the present program for tension, torsion, fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion measurements.

A.2 Fabrication of Tension Specimens

All tension specimens were prepared using a 17.75 cm x 17.75 cm x 22 cm steel box mold shown in Figure A1a. This box mold allows the casting of 32 specimens at one time, each 1.52 cm wide by 0.254 cm thick. As can be seen in both Figure A1a and Figure A1b, thin polished steel dividers are spaced equally in the bottom of the box mold using small steel spacers at each end. All steel pieces were sprayed at room temperature with a fast drying aerosol release agent, Miller-Stephenson MS-122, prior to assembling the mold. The assembled mold was preheated to 99°C in an oven. When the mold reached 100°C, a weighed quantity (up to 300 grams) of frozen resin was placed in the mold and the assembly was placed in a vacuum oven at 100°C. When the resin was completely melted, a vacuum was drawn on the system. The resin foamed vigorously



a.) Steel Box Mold With Dividers and Spacers.



b.) Steel Dividers and Spacers Used in Box Molds.

Figure A1. Steel Box Mold Used to Cast Flat Neat Resin Specimen Blanks.

and care was required to prevent overflowing the mold. This step was necessary to remove entrapped air and volatiles from the resin and is the reason for such a tall mold wall. Vacuum was continued until the resin was free of air and bubbles in the bottom of the mold. Then excess resin above the steel dividers was squeegeed off and the mold placed in an air-circulating oven at approximately 135°C for 5 hours. The mold was then disassembled and the individual moldings sanded to remove flashing. The moldings were then placed in a preheated oven while being held snugly between two smooth pieces of steel and postcured at 177°C between 1 and 5 hours depending upon the resin. An auxiliary thermocouple was placed on the surface of one of the specimens to ensure proper temperature control for the entire time. After postcure, the specimens wre ground to uniform widths using a surface grinder. The tensile bars were then placed in a jig and routed with a diamond-coated router bit to the proper dogbone shape. The specimens were then placed in desiccators or moisture chambers for storage or moisture saturation. Finished tensile specimens are shown in Figure A2.

A.3 Fracture Toughness Specimen Casting Procedure

The notched-bend toughness specimens were cast in a similar fashion as the tensile specimens. Only the small spacers were changed in the square steel mold to allow nineteen 0.635 cm thick specimens to be cast. The 1.52 cm width was sufficient for these fracture toughness specimens. After grinding the specimens, three notches were cut in one side of the specimen to approximately one-half the width. Figure A3 is a photograph of the fracture toughness bars with notches cut. Three independent tests can be made from one bar since the span in the three-point bend fixture is only 5.00 cm and the two outer notches are totally out of the loading

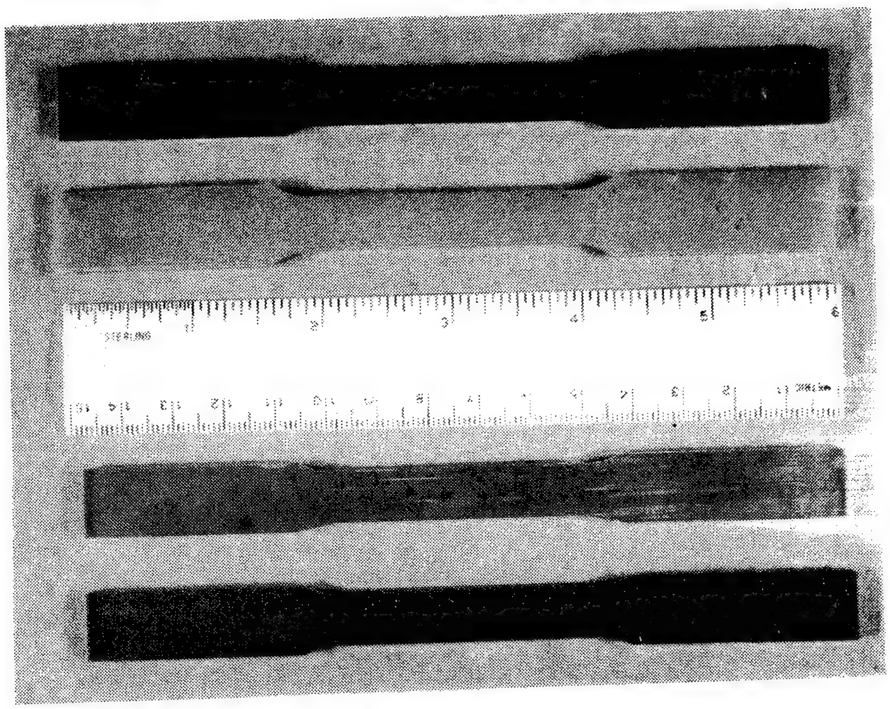


Figure A2. Typical Tensile Specimens Routed to the Required Dogbone Shape.

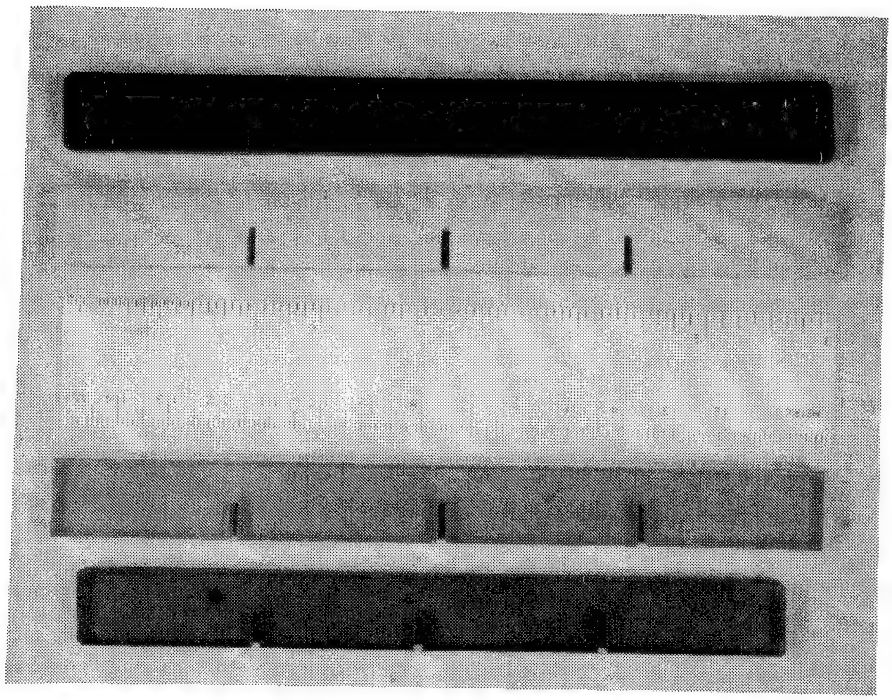


Figure A3. Typical Notched Bend Fracture Toughness Specimens.

area.

A.4 Fabrication of Thin Flat Specimens

Coefficient of moisture expansion (CME) specimens were cast in the same square steel box molds used for the tensile bars, without spacers or dividers. Approximately 100 grams of frozen resin was placed in the preheated mold and the curing times and temperatures duplicated from the tensile bar casting procedure. This mold yielded four specimens about 0.125 cm thick and 7 cm square after cutting the large square piece using a diamond-coated saw blade. A surface grinder was used to reduce the thickness to the 0.080 cm thickness used in the experiments. Figure A4 is a photograph of typical specimens used in this program.

Large flat specimens were also fabricated using procedures similar to those used for the CME specimens. Approximately 200 grams of frozen resin were used in an open box mold to make one 17 cm x 17 cm x 0.32 cm specimen for each of the four resin systems.

A.5 Fabrication of Cylindrical Torsion Specimens

The Hercules 3502, 2220-1, and 2220-3 epoxies were cast using single-cavity split steel molds which were ground to the required dogbone shape. Figure A5 contains photographs of these steel molds. As can be seen in the figure, the mold consisted of three pieces screwed together to form the mold cavity. A silicone rubber funnel (Figure A5b) was placed over the open end of the mold and the mold preheated to 100°C after being sprayed with the Miller-Stephenson release agent. Figure A5b shows the assembled mold and rubber funnel. Approximately 21 grams of frozen resin were placed in the rubber funnel and allowed to melt into the mold. A vacuum was then pulled in the oven and regulated to prevent foam from overflowing the funnel. When the resin had been sufficiently

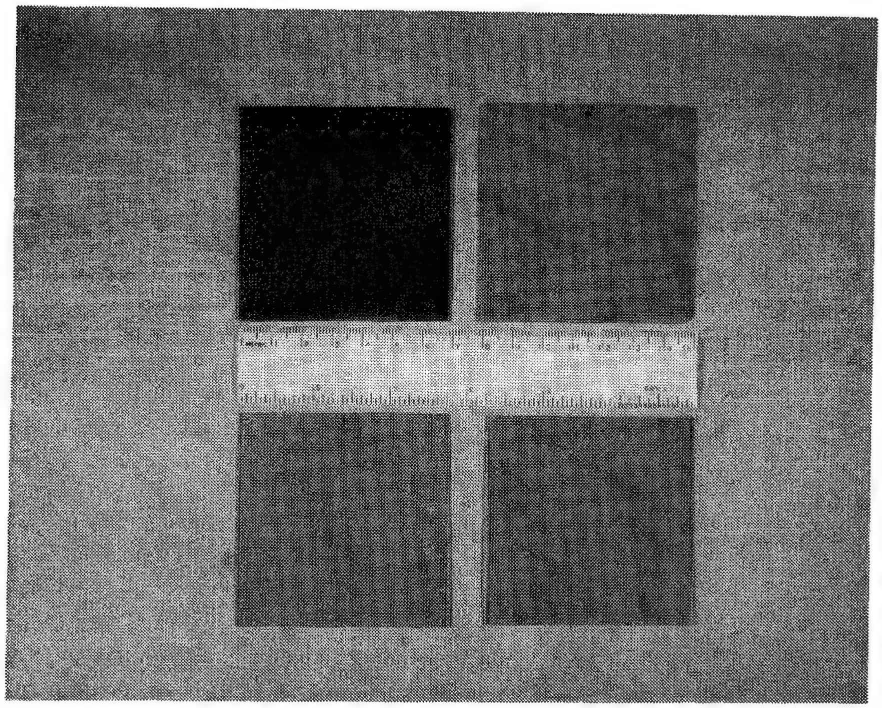
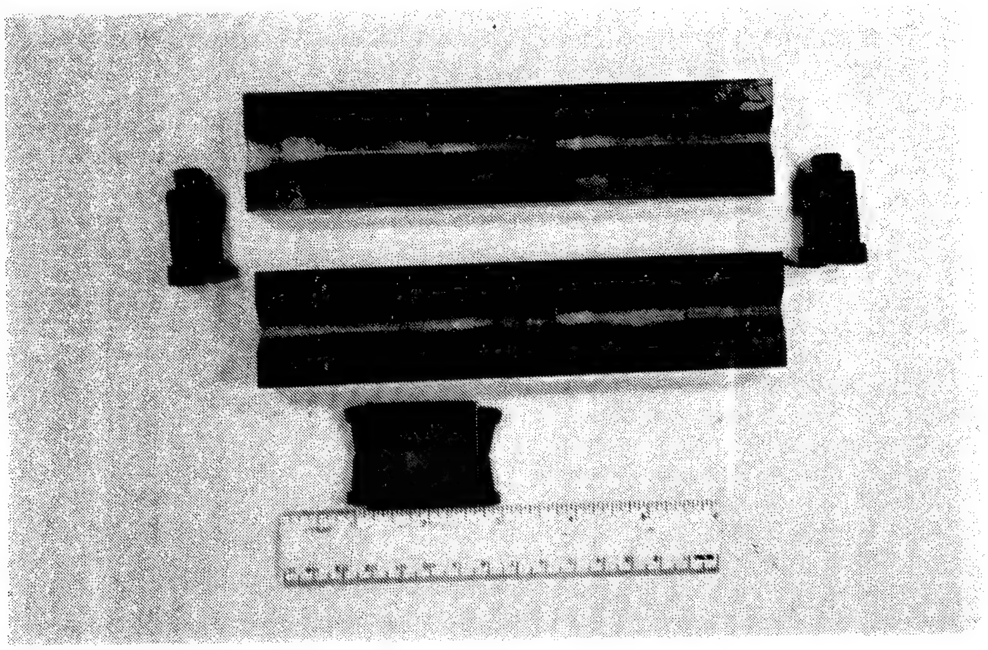
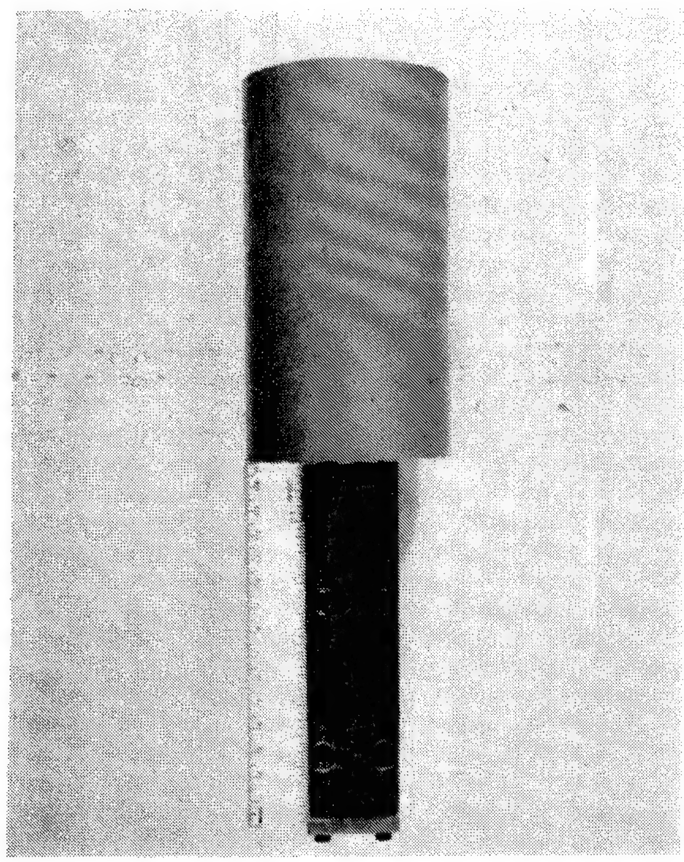


Figure A4. Typical Coefficient of Moisture Expansion (CME) Specimens.



a.) Split Steel Mold Unassembled (Fastener Bolts also Shown).



b.) Assembled Mold With Rubber Funnel on Top for Holding Resin During Melting and Volatiles Removal.

Figure A5. Split Steel Mold Used to Cast Cylindrical Dogbone Specimens.

degassed, which required about 20-30 minutes, the molds were placed in an air-circulating oven at 135°C with the rubber funnels removed. The specimens were cured for 2-5 hours, depending on the resin system, and then removed from the split molds after being allowed to cool. The round dogbones were then postcured at 177°C, placing them between two stiff rubber sheets having a middle rib to support the center section should the specimens become slightly soft during postcure. A thermocouple was placed between the sheets to monitor specimen temperature and ensure the epoxy was maintained at the proper temperature.

After postcuring, the round specimens were polished with 400-grit and then 600-grit wet/dry emery paper using a small lathe to turn the specimens. This process removed all mold flashing and produced a consistent finish for all test specimens. After inspection the specimens were labeled and placed in desiccators or environmental chambers as appropriate for proper conditioning. Figure A6 shows typical round dogbone specimens ready for torsion testing.

The Fibredux 914 epoxy required slightly different processing to assure a reasonable test specimen without bubbles or voids. Silicone rubber molds were cast around a steel mandrel shaped to the round dogbone form. This produced a hard rubber form to cast the 914 epoxy in. The rubber molds were slit longitudinally to remove the steel mandrel, using a sharp knife, and the internal surface of the rubber mold was inspected for defects. After inspection the rubber molds were used in the same fashion as the steel molds to cast the 914 specimens. After curing, the 914 specimens were removed from the slit rubber molds and fully cured for one hour at 177°C held between the flat rubber sheets used with the other three resin systems. The 914 epoxy presented more

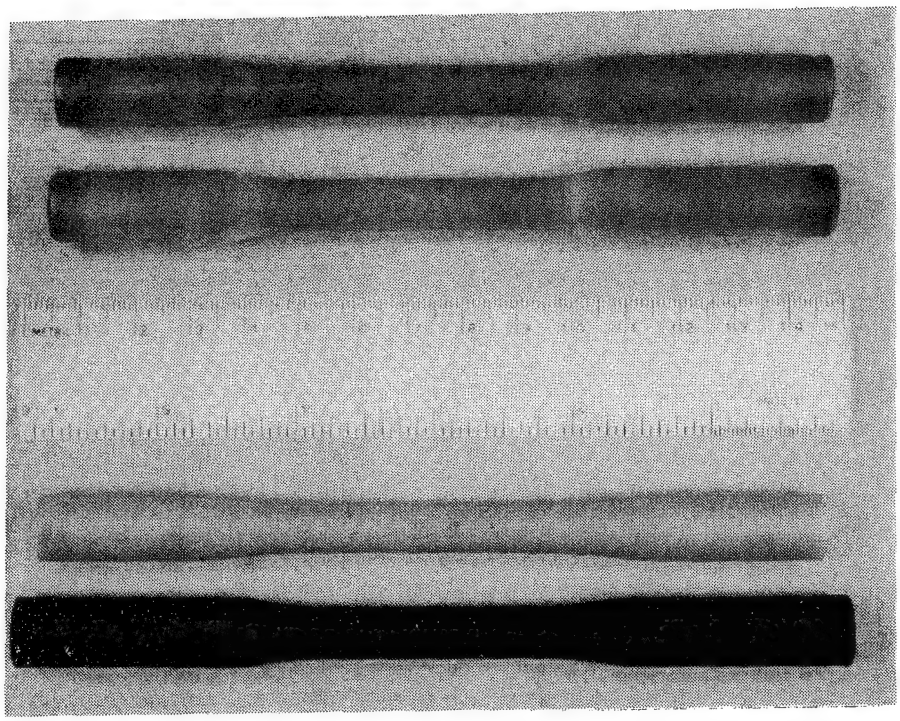


Figure A6. Typical Cylindrical Dogbone Specimens Used for Torsion Testing.

problems in the casting process due to its greater degree of shrinkage during cure. The rubber molds, having a much higher coefficient of thermal expansion, better compensated for the shrinkage in the 914 epoxy than the steel molds. A rubber mold is shown cut into two halves for viewing purposes in Figure A7.

A.6 Problems

Several problems in resin casting were encountered during this program. The 914 epoxy shrank more than the three other systems and seemed to be much more sensitive to processing temperature, i.e., it had a strong tendency to increase in viscosity before the air and volatiles had been fully removed. This resulted in more rejected specimens.

Some evidence of foreign particle contamination was encountered in all four resin systems. The fabrication process used by the Composite Materials Research Group was carefully monitored; it was concluded that the foreign particles were present in the frozen resin when received from the manufacturers and could not be removed by filtration prior to molding because of the high viscosity of these resins. These foreign particles occurred in the gage section of about one out of every twenty cast resin specimens. These specimens were discarded.

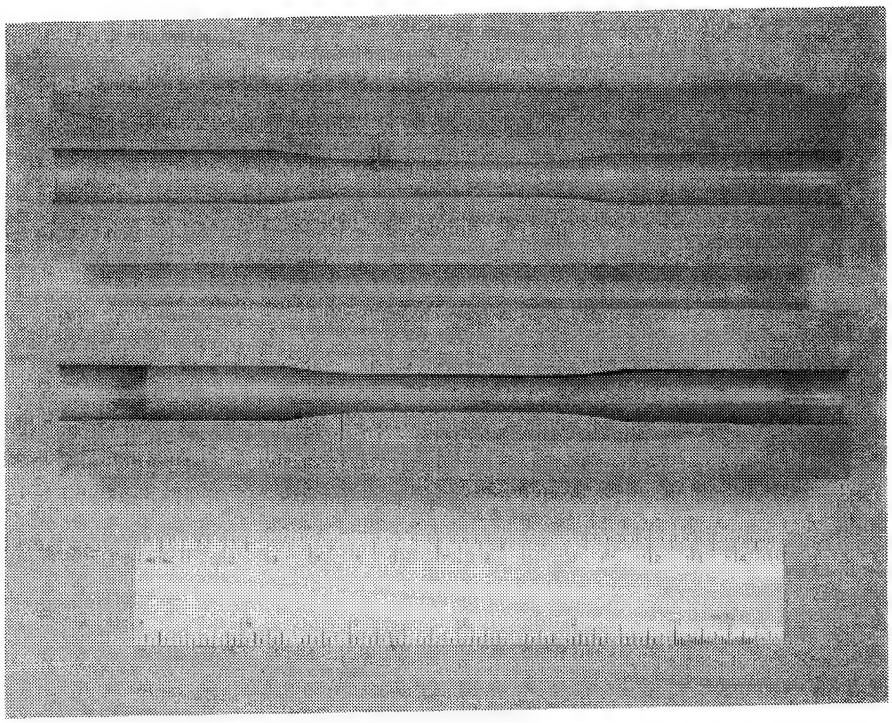


Figure A7. Silicone Rubber Mold Cut into Two Halves to Show the Dogbone Shape.

APPENDIX B

TEST METHODS

B.1 Tension Test Method

Tension tests were performed in an Instron Model 1125 electromechanical testing machine, using a loading rate of 2 mm/min. All data were recorded on a Hewlett-Packard HP 21 MX-E minicomputer which was used to plot the stress-strain curves presented in Appendix C. Tensile strains were measured using an extensometer or strain gage rosette depending on moisture conditioning and test temperature. Only an extensometer was used with the moisture-saturated specimens because of problems with gage adherence to the moisture-saturated surface. A transverse extensometer was used in conjunction with the longitudinal extensometer for calculation of Poisson's ratio. Figure B1 shows a typical test set-up using longitudinal and transverse extensometers. A 0°/90° strain gage rosette was used on all the dry specimens to measure the longitudinal and transverse strains. To verify that both of the strain measurement methods would yield equivalent strains on these materials of fairly low moduli, the room temperature, dry specimens were tested using both extensometers and strain gage rosettes.

Wedge grips were used on the flat dogbone tensile specimens. A 120-grit emery cloth was used in the grips to reduce the stress concentrations induced by the serrations on the grip faces, thereby avoiding the tendency of the neat resin specimens to fail in the grip area.

The dry neat resin specimens were stored in a desiccator to ensure the specimens remained dry. The moisture-saturated specimens were conditioned in a glass container filled with distilled water to a level

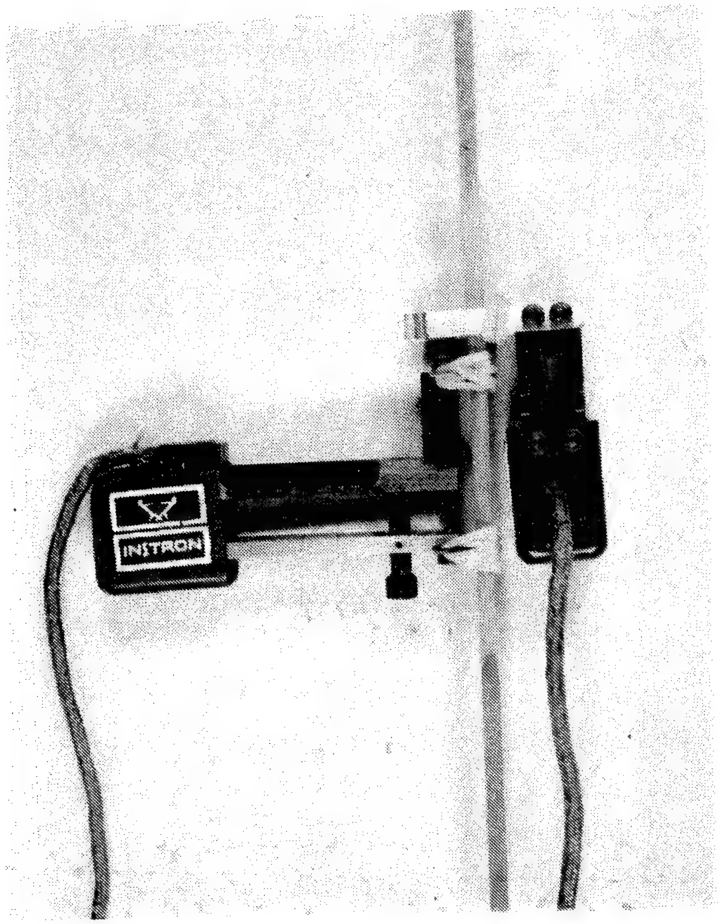


Figure Bl. Typical Tension Test Setup With Two Extensometers.

The longitudinal extensometer with a one-inch gage length is on the left. The transverse extensometer is on the right using the specimen width as its gage length.

just below where the specimens were suspended, to maintain approximately 98% relative humidity. A temperature of 74°C was maintained by placing the container in a Tenney Benchmaster environmental chamber. Periodic weighings of witness specimens were done to determine when saturation of the neat resin specimens was achieved. After they reached saturation the specimens were removed from the elevated temperature chamber and stored in moist containers at room temperature to maintain them at their equilibrium levels. The specimens were moved in a beaker of water to the test machine in groups of five to ensure a moisture-saturated condition was maintained up to the point of the actual test. Only for the short time required to place the specimens in the grips and then perform the test were they in a dry environment.

A BEMCO environmental chamber was used for elevated temperature tests. This chamber has a temperature range from -129°C to 438°C. Three test temperatures were chosen for this program, viz, 23°C, 54°C, and 82°C.

B.2 Torsion Test Method

Solid rod torsion tests were performed in an Instron Model 1125 electromechanical testing machine configured for torsion testing. Collets were used to grip the round specimens with 120-grit emergy paper being used to minimize the stress concentration on the test specimen and minimize slippage.

Angle of twist was measured using a "rotometer" developed at the University of Wyoming for this purpose. Two cams are attached to the specimen and an arrangement of four LVDT's convert the rotary movement into proportional linear signals. These signals are then subtracted in a Daytronix Model 9132 amplifier module to yield shear strain for input to

the 21MX-E minicomputer. Figure B2 shows the specimen, cam and LVDT arrangement. A BEMCO environmental chamber was used for the elevated temperature.

B.3 Fracture Toughness Test Method

Fracture toughness testing was performed using ASTM Standard E 399-81. A three-point bend fixture was fabricated from the specifications found in the ASTM standard and is shown in Figure B3. A razor blade was used to scribe the notch tip. A fixture was developed to ensure the razor blade would cut the specimens equally when drawn through the fixture. Figure B4 is a photograph showing the razor blade held in a spring loading arm. The fixture was held firmly and the specimen drawn through the blade, providing a uniform cut at the notch tip. The specimens were then placed in the test fixture and loaded to failure while recording the loading history. Calculation of the plane strain fracture toughness K_{IC} was done using the following equation:

$$K_{IC} = \frac{3PL}{BW^2} a^{\frac{1}{2}}[1.93-3.07(\tfrac{a}{W})+14.53(\tfrac{a}{W})^2-25.11(\tfrac{a}{W})^3+25.80(\tfrac{a}{W})^4]$$

where P = load

L = specimen length

W = specimen width

B = specimen thickness

a = length of pre-crack and notch

The critical strain energy release rate G_{IC} is calculated from the following equation:

$$G_{IC} = \frac{K_{IC}^2}{E}$$

where E = elastic modulus

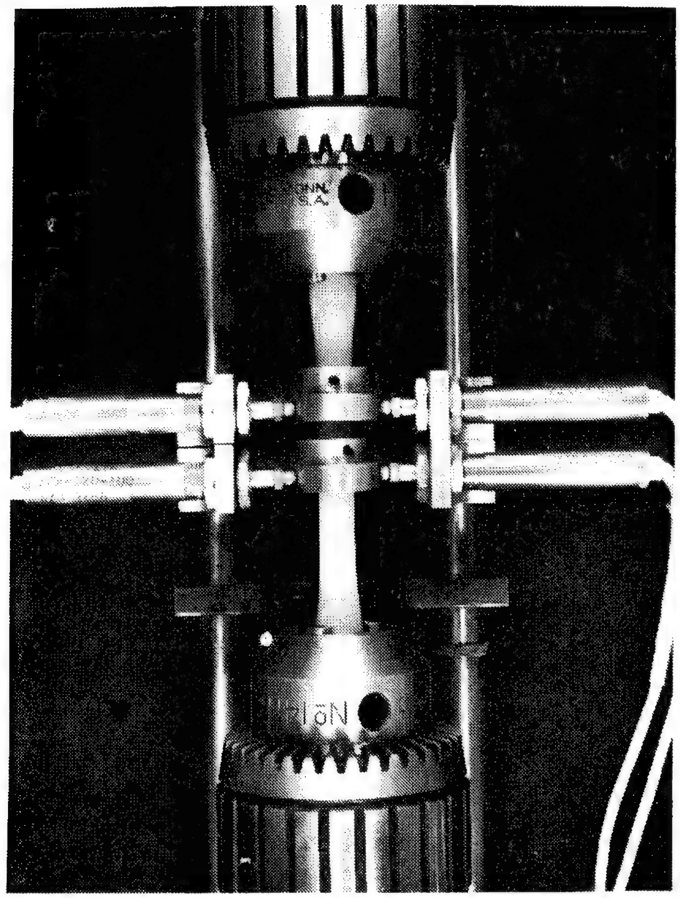


Figure B2. Torsional Shear Test Setup Showing Rotometer Mounted on Specimen.

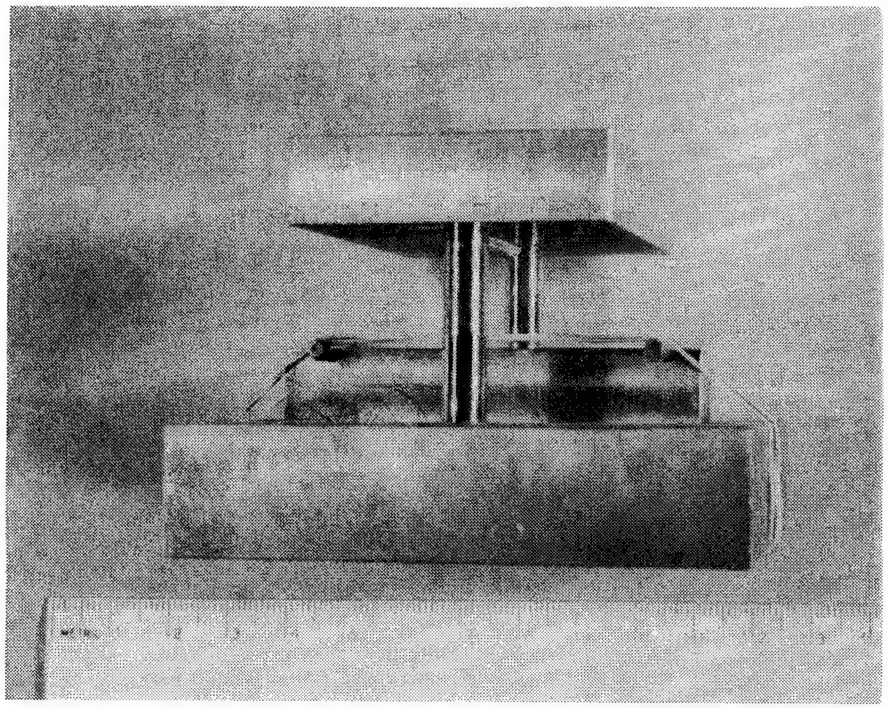


Figure B3. Single-Edge Notch Bend Test Fixture.

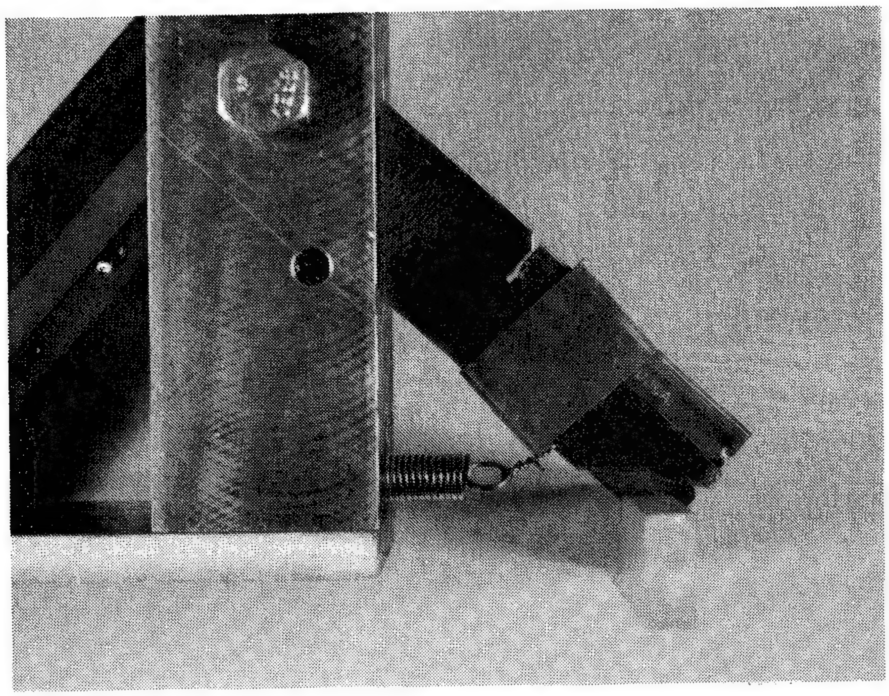


Figure B4. Notch Crack Initiator Apparatus For Single-Edge Notch Bend Test Specimen.

B4. Coefficient of Thermal Expansion Test Method

Coefficient of thermal expansion (CTE) measurements were performed using a glass tube dilatometer linked to an LVDT. Figure B5 is a photograph of the test apparatus. The LVDT signal was amplified through a Daytronics Model 9130 amplifier and then to the Y-axis of a Hewlett-Packard Model 7004-B X-Y plotter. Temperature change was monitored using a T-type thermocouple attached to the specimen and amplified through a Daytronics Model 9110 AT module and then to the X-axis of the Hewlett-Packard Model 7004B X-Y plotter. A plot of expansion vs. temperature was thus generated. A heat-up rate of 1.1°C/min was used, over a range from room temperature to 93°C. Dry and moisture-saturated specimens were tested to determine the change in CTE due to moisture absorption. After the tests were completed, the data points were input to a computer curve-fit routine and an equation for the nonlinear CTE behavior was calculated. These equations were subsequently used in the micromechanics analysis program.

B.5 Coefficient of Moisture Expansion Test Method

Coefficient of moisture expansion (CME) measurements were performed on the four unreinforced epoxy systems using a glass tube dilatometer/LVDT apparatus to measure moisture expansion and an electronic balance to concurrently measure the weight gain of an identical witness specimen hung within the same environmental chamber. A photograph of the three-station apparatus is shown in Figure B6.

Moisture conditions were maintained by means of distilled water in open containers inside a plexiglass insert in the test ovens. A T-type thermocouple placed close to the two specimens monitored the constant 66°C temperature during the tests.

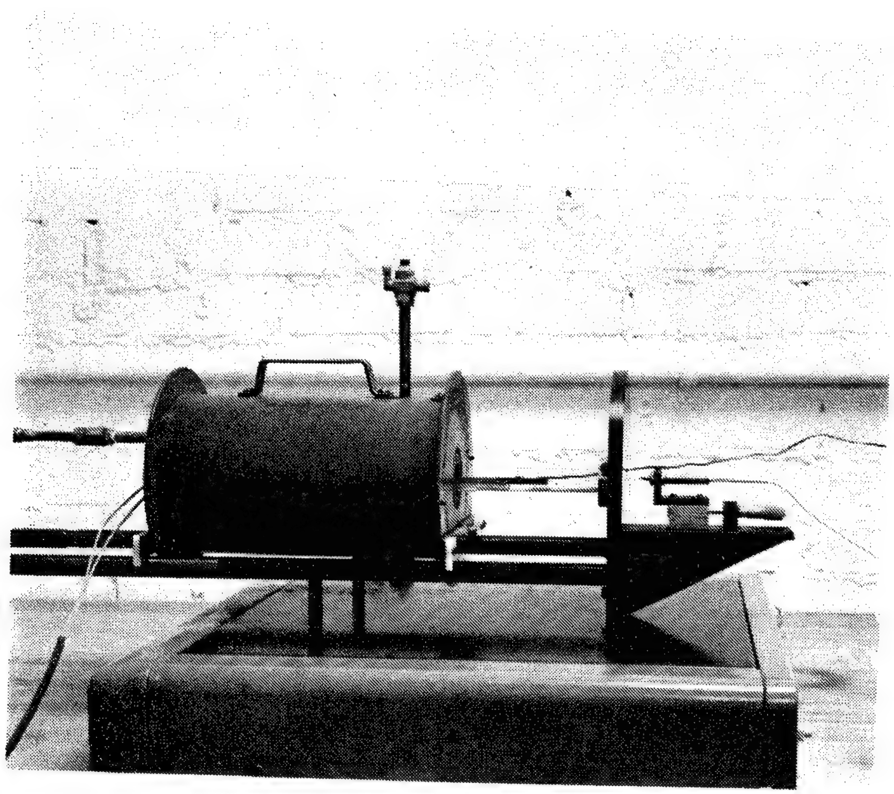


Figure B5. Coefficient of Thermal Expansion Test Apparatus.

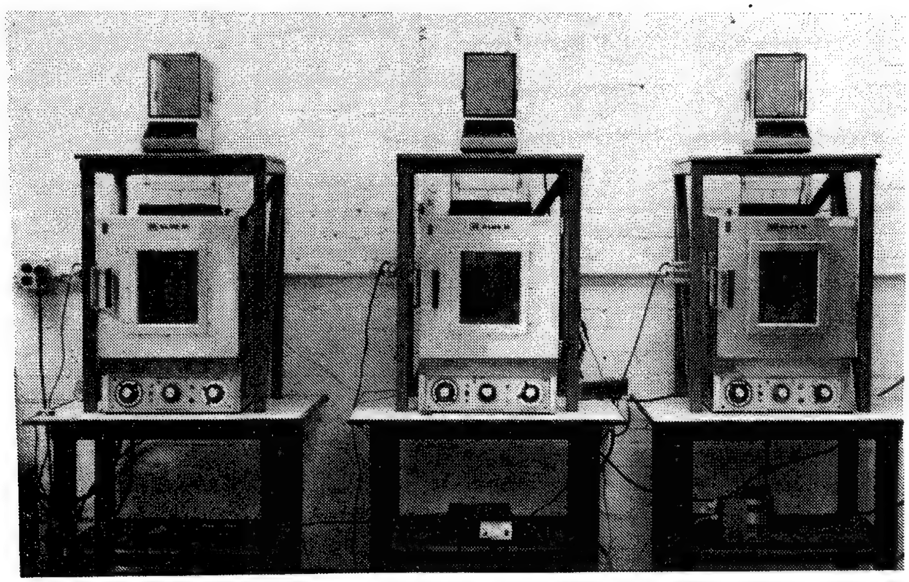


Figure B6. Coefficient of Moisture Expansion Test Apparatus.

A hole was drilled through the top of each oven to allow a linkage to a Sartorius balance mounted above, for weight gain measurement. A hole drilled in the side of each oven allowed the passage of the quartz glass rod of a dilatometer to the LVDT assembly for measurement of moisture expansion.

A 7 cm x 7 cm x 0.08 cm specimen configuration was used which was large enough to permit the assumption of one-dimensional moisture diffusion and the calculation of β, the coefficient of moisture expansion. The specimens were surface ground to size and then dried in a desiccator maintained at 93°C prior to testing to ensure a dry initial state.

Data were periodically recorded and then input to a computer curve-fit routine to calculate the relation to best fit the data. These equations were subsequently input to the micromechanics analysis program to predict moisture effects in the graphite/epoxy composites.

APPENDIX C

INDIVIDUAL TEST RESULTS AND STRESS-STRAIN CURVES FOR EACH TEST CONDITION

All test results were included in an initial average. If the standard deviation was greater than 10%, all values falling outside this standard deviation were removed, noted with an asterisk, and a new average and standard deviation were calculated.

TABLE C1

INDIVIDUAL 3502 DRY TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTDA 31	23	40.0	5.8	0.011	3.65	0.53	0.37
32		31.7*	4.6*	0.009	3.65	0.53	0.37
33		35.1	5.1	0.009	3.79	0.55	0.36
34		32.4	4 7	0.009	3.86	0.56	0.39
35		37.2	5.4	0.010	3.86	0.56	0.37
36		43.4*	6.3*	0.012	3.65	0.53	0.35
37		40.7	5.9	0.012	3.45	0.50	0.34
average		37.2	5.4	0.010	3.65	0.53	0.36
standard deviation		3.5	0.5	0.001	0.14	0.02	0.02
LTDB 31	54	30.3	4.4	0.007	3.31	0.48	0.36
32		28.3	4.1	0.009	3.24	0.47	0.38
33		24.1*	3.5*	0.007	3.31	0.48	0.36
34		31.7	4.6	0.011	3.31	0.48	0.36
35		37.2*	5.4*	0.011	3.17	0.46	0.36
average		30.3	4.4	0.009	3.24	0.47	0.36
standard deviation		1.7	0.3	0.002	0.07	0.01	0.01
LTDC 31	82	32.4	4.7	0.009*	3.17	0.46	0.35
32		39.3	5.7	0.013	3.10	0.45	0.37
33		54.5*	7.9*	0.019	3.10	0.45	0.39
34		46.2	6.7	0.016	3.17	0.46	0.37
35		40.7	5.9	0.014	3.03	0.44	0.36
average		42.1	6.1	0.016	3.10	0.45	0.37
standard deviation		3.6	0.5	0.002	0.07	0.01	0.01

* Not included in average

TABLE C2

INDIVIDUAL FIBREDUX 914 DRY TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTDA 21	23	25.5	3.7	0.006	4.27	0.62	0.38
22		29.6	4.3	0.007	4.48	0.65	0.38
23		29.6	4.3	0.007	4.00	0.58	0.37
24		22.8*	3.3*	0.006	4.00	0.58	0.36
25		22.8*	3.3*	0.006	4.00	0.58	0.37
26		24.8	3.6	0.009	3.86	0.56	0.35
27		33.8*	4.9*	0.009	3.79	0.55	0.34
28		31.7	4.6	0.009	3.65	0.53	0.34
average		28.3	4.1	0.007	4.02	0.58	0.36
standard deviation		2.9	0.4	0.001	0.28	0.04	0.02
LTDB 21	54	36.5*	5.3*	0.011	3.31	0.48	0.36
22		28.9	4.2	0.009	3.38	0.49	0.35
23		31.0	4.5	0.009	3.45	0.50	0.38
24		31.0	4.5	0.007	3.31	0.48	-
25		29.0	4.2	0.009	3.38	0.49	0.36
average		30.3	4.4	0.009	3.37	0.49	0.36
standard deviation		1.2	0.2	0.001	0.06	0.01	0.01
LTDC 21	82	40.1*	5.9*	0.014	3.10	0.45	0.36
22		31.7	4.6	0.010	3.31	0.48	0.37
23		30.3	4.4	0.010	2.96	0.43	0.36
24		33.1	4.8	0.012	2.89	0.42	0.37
25		14.5*	2.1*	0.004*	3.52	0.51	0.37
average		31.7	4.6	0.012	3.17	0.46	0.37
standard deviation		1.4	0.2	0.002	0.28	0.04	0.01

* Not included in average

TABLE C3

INDIVIDUAL 2220-1 DRY TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTDA 01	23	42.7	6.2	0.004*	9.72*	1.41*	0.34
2		42.7	6.2	0.014	2.55	0.37	0.37
3		44.1	6.4	0.014	3.31	0.48	0.37
4		41.4	6.0	0.014	3.03	0.44	0.36
5		45.5	6.6	0.015	3.10	0.45	0.36
average		43.4	6.3	0.014	2.96	0.43	0.36
standard deviation		1.4	0.2	0.001	0.34	0.05	0.01
LTDB 01	54	57.2	8.3	0.008*	2.96	0.43	0.19*
2		49.6	7.2	0.020	2.90	0.42	0.38
3		60.7	8.8	0.019	2.96	0.43	0.36
4		49.0*	7.1*	0.015	3.17	0.46	0.38
5		68.9*	10.0*	0.019	2.96	0.43	0.37
average		55.8	8.1	0.018	2.96	0.43	0.37
standard deviation		5.6	0.8	0.002	0.07	0.01	0.01
LTDC 01	82	73.8	10.7	0.024	2.48	0.36	0.19
2		71.7	10.4	0.038*	2.48	0.36	0.38
3		73.8	10.7	0.006*	2.83	0.41	0.36
4		50.3*	7.3*	0.015	2.48	0.36	0.38
5		51.7*	7.5*	0.023	2.83	0.41	0.37
average		73.1	10.6	0.021	2.62	0.38	0.36
standard deviation		1.2	0.2	0.005	0.21	0.03	0.02

* Not included in average

TABLE C4

INDIVIDUAL 2220-3 DRY TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTDA 11	23	25.5*	3.7*	0.008*	3.24	0.47	0.37
12		42.7	6.2	0.014	3.17	0.46	0.37
13		45.5	6.6	0.015	3.10	0.45	0.34
14		35.1	5.1	0.011	3.31	0.48	0.37
15		51.7	7.5	0.017	3.38	0.49	0.37
16		51.0	7.4	0.018	3.24	0.47	0.36
17		64.1*	9.3*	0.025*	2.96	0.43	0.35
average		45.5	6.6	0.015	3.17	0.46	0.36
standard deviation		6.8	1.0	0.003	0.14	0.02	0.01
LTDB 11	54	59.3	8.6	0.027	2.69	0.39	0.33
12		82.0*	11.9*	0.038*	2.96	0.43	0.37
13		51.7	7.5	0.018*	3.45	0.50	0.42
14		49.6	7.2	0.021	2.96	0.43	0.35
15		66.9	9.7	0.030	2.83	0.41	0.35
average		56.5	8.2	0.026	2.96	0.43	0.36
standard deviation		7.9	1.1	0.004	0.28	0.04	0.03
LTDC 11	82	54.5*	7.9*	0.029	2.48	0.36	0.39
12		73.1	10.6	0.018	2.62	0.38	0.36
13		64.8	9.4	0.031	2.28	0.33	0.34
14		71.0	10.3	0.018	2.48	0.36	0.34
15		71.7	10.4	0.036*	2.41	0.35	0.35
average		70.3	10.2	0.024	2.45	0.36	0.35
standard deviation		3.7	0.5	0.007	0.13	0.02	0.02

* Not included in average

TABLE C5

INDIVIDUAL 3502 WET TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTWA 31	23	37.2	5.4	0.011	3.45	0.50	0.42
32		33.1	4.8	0.011	3.38	0.49	0.42
33		34.4	5.0	0.010	3.79	0.55	0.43
34		37.9	5.5	-	-	-	-
35		44.8*	6.5*	0.014	3.52	0.51	0.44
average		35.9	5.2	0.012	3.52	0.51	0.43
standard deviation		2.3	0.3	0.001	0.14	0.02	0.01
LTWB 31	54	26.2	3.8	0.009	2.96	0.43	0.40
32		22.8	3.3	0.008	3.03	0.44	-
33		32.4*	4.7*	0.012*	2.96	0.43	0.38
34		21.4	3.1	0.007	2.96	0.45	0.38
35		22.1	3.2	0.007	3.10	0.45	0.38
average		22.8	3.3	0.008	3.03	0.44	0.38
standard deviation		2.0	0.3	0.001	0.07	0.01	0.01
LTWC 31	82	19.3*	2.8*	0.008	2.55	0.37	0.41
32		25.5	3.7	0.011	2.43	0.36	0.40
33		27.6*	4.0*	0.011	2.48	0.36	0.42
34		24.8	3.6	0.009	2.76	0.40	0.45
35		24.1	3.5	0.010	2.55	0.37	0.44
36		24.8	3.6	-	-	-	-
average		24.8	3.6	0.010	2.58	0.37	0.42
standard deviation		0.6	0.1	0.001	0.14	0.02	0.02

* Not included in average

TABLE C6

INDIVIDUAL FIBREDUX 914 WET TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTWA 21	23	40.0	5.8	0.014	3.03	0.44	0.44
22		32.4*	4.7*	0.010*	3.24	0.47	0.44
23		54.5	7.9	0.020	3.10	0.45	0.43
24		44.8	6.5	0.016	3.03	0.44	0.40
25		53.8	7.8	0.019	3.03	0.44	0.44
average		48.3	7.0	0.017	3.10	0.45	0.43
standard deviation		7.1	1.0	0.003	0.70	0.01	0.02
LTWB 21	54	31.7	4.6	0.011	3.31	0.39	0.43
22		31.7	4.7	0.009	3.38	0.37	0.40
23		27.6	4.0	0.009	3.45	0.37	0.41
24		32.4	4.7	0.007	3.31	0.37	0.45
25		31.7	4.6	0.009	3.38	0.36	0.41
26		35.2	5.1	-	-	-	-
average		31.8	4.6	0.009	2.56	0.37	0.42
standard deviation		2.4	0.4	0.001	0.70	0.01	0.02
LTWC 21	82	35.9	5.2	0.020*	2.14	0.31	0.41
22		31.7	4.6	0.017	2.07	0.30	0.41
23		29.6	4.3	0.014	2.28	0.33	0.40
24		31.7	4.6	0.017	2.00	0.29	0.39
25		30.3	4.4	0.015	2.14	0.31	0.38
average		31.7	4.6	0.016	2.14	0.31	0.40
standard deviation		2.1	0.3	0.002	0.70	0.01	0.01

* Not included in average

TABLE C7

INDIVIDUAL 2220-1 WET TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTWA 01	23	62.1	9.0	0.024	3.10	0.45	0.40
2		62.1	9.0	0.025	3.03	0.44	0.39
3		81.4*	11.8*	0.029	3.17	0.46	0.41
4		79.5	11.5	0.034	3.17	0.46	0.42
5		68.3	9.9	0.029	3.10	0.45	0.41
average		68.3	9.9	0.028	3.11	0.45	0.41
standard deviation		8.3	1.2	0.004	0.06	0 01	0.01
LTWB 01	54	52.4	7.6	0.026	2.76	0.40	0.46
2		53.8	7.8	0.030	2.48	0.36	0.42
3		57.9	8.4	0.034	2.55	0.37	0.43
4		57.9	8.4	0.034	2.48	0.36	0.42
5		62.1	9.0	0.038	2.56	0.37	0.43
average		56.5	8.2	0.032	2.56	0.37	0.43
standard deviation		4.1	0.6	0.004	0.12	0.02	0.02
LTWC 01	82	46.2	6.7	0.038	2.14	0.31	0.44
2		45.5	6.6	0.034	2.00	0.29	0.41
3		46.2	6.7	0.037	2.07	0.30	0.42
4		45.5	6.6	0.033	2.00	0.29	0.43
5		47.6	6.9	0.042	2.07	0.30	0.43
average		46.2	6.7	0.037	2.07	0.30	0.43
standard deviation		0.7	0.1	0.003	0.07	0.01	0.01

* Not included in average

TABLE C8

INDIVIDUAL 2220-3 WET TENSION RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)	Poisson's Ratio
LTWA 11	23	75.1	10.9	0.036	3.03	0.44	0.44
12		54.5	7.9*	0.020*	3.03	0.44	0.36
13		61.4	8.9	0.024	3.17	0.46	0.44
14		82.7	12.0*	0.034	3.10	0.45	0.43
15		63.4	9.2	0.037	2.96	0.43	0.45
average		66.7	9.7	0.033	3.03	0.44	0.43
standard deviation		7.4	1.1	0.006	0.07	0.01	0.03
LTWB 11	54	63.4	9.2	0.037	2.55	0.37	0.46
12		62.7	9.1	0.043	2.48	0.36	0.42
13		55.8	8.1	0.032	2.55	0.37	0.43
14		64.1	9.3	0.051*	2.41	0.35	0.31*
15		-	-	0.035	2.21	0.32	-
average		61.4	8.9	0.037	2.41	0.35	0.44
standard deviation		4.1	0.6	0.005	0.14	0.02	0.02
LTWC 11	82	37.9	5.5	0.052	2.28	0.33	0.45
12		46.2	6.7	0.068*	2.00	0.29	0.49
13		43.4	6.3	0.042	2.00	0.29	0.46
14		44.1	6.4	0.049	2.21	0.32	0.46
15		48.3	7.0	0.048	2.34	0.34	0.49
average		44.1	6.4	0.048	2.14	0.31	0.47
standard deviation		3.9	0.6	0.004	0.14	0.02	0.02

* Not included in average

TABLE C9

INDIVIDUAL 3502 DRY SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Shear Modulus (GPa)	Shear Modulus (Msi)
LSDA 31	23	33.8	4.9*	0.022	1.59	0.23
32		64.8	9.4	0.042	2.07	0.30
33		46.9	6.8	0.014*	2.07	0.30
34		68.3	9.9	0.047	1.52	0.22
35		41.4*	6.0*	0.028	1.59	0.23
36		79.3*	11.5*	0.051*	2.27*	0.33*
37		63.4	9.2	0.040	1.86	0.27
38		57.2	8.3	0.039	1.45*	0.21*
average		60.0	8.7	0.036	1.79	0.26
standard deviation		8.3	1.2	0.009	0.20	0.03
LSDB 31	54	90.3*	13.1*	0.067	1.59	0.23
32		61.4	8.9	-	1.79*	0.26*
33		69.6	10.1	0.057	1.03*	0.15*
34		62.0	9.0	0.043	1.52	0.22
35		76.5	11.1	0.060	1.59	0.23
average		67.6	9.8	0.057	1.59	0.23
standard deviation		6.9	1.0	0.010	0.03	0.01
LSDC 31	82	71.0	10.3	0.058	1.52	0.22
32		73.1	10.6	0.055	1.59	0.23
33		60.0	8.7	0.047	1.59	0.23
34		57.9*	8.4*	0.040*	1.52	0.22
35		75.8	11.0	0.058	1.59	0.23
average		70.4	10.2	0.055	1.59	0.23
standard deviation		7.0	1.0	0.005	0.03	0.01

* Not included in average

TABLE C10

INDIVIDUAL FIBREDUX 914 DRY SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSDA 21	23	81.4	11.8	0.072	1.17*	0.17*
22		74.5	10.8	0.050	1.86	0.27
23		60.7*	8.7*	0.040	1.52	0.22
24		83.4	12.1	0.074	1.24	0.18
25		88.9*	12.9*	0.061	1.59	0.23
26		59.3*	8.6*	0.035*	2.00*	0.29*
average		80.0	11.6	0.059	1.52	0.22
standard deviation		4.8	0.7	0.014	0.28	0.04
LSDB 21	54	63.4	9.2	0.049	1.59	0.23
22		54.5	7.9	0.039	1.52	0.22
23		86.2*	12.5*	0.068*	1.72	0.25
24		55.2	8.0	0.046	1.38	0.20
25		68.3	9.9	0.045	1.45	0.21
average		60.7	8.8	0.045	1.52	0.22
standard deviation		6.8	1.0	0.004	0.14	0.02
LSDC 21	82	51.7*	7.5*	-	0.83	0.12
22		69.6	10.1	0.055	1.45	0.21
23		73.1	10.6	0.070	0.76*	0.11*
24		76.5	11.1	0.059	1.59	0.23
25		95.8	13.9*	0.060	1.52	0.22
26		81.4*	11.8	-	-	-
average		75.1	10.9	0.061	1.17	0.20
standard deviation		5.0	0.7	0.006	0.41	0.06

* Not included in average

TABLE C11

INDIVIDUAL 2220-1 DRY SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSDA 01	23	47.6*	6.9*	0.012*	-	-
2		71.7	10.4	0.042	-	-
3		32,4*	4.7*	0.022	1.52	0.22
4		85.5	12.4	0.098	1.65	0.24
5		68.9	10.0	0.056	1.65	0.24
6		90.3	13.1	0.096	0.97*	0.14*
7		66.2	9.6	0.055	1.45	0.21
8		100.6*	14.6*	0.126*	1.38	0.20
average		76.5	11.1	0.062	1.52	0.22
standard deviation		10.7	1.6	0.030	0.14	0.02
LSDB 01	54	67.6	9.8	0.067	1.38	0.20
2		86.9	12.6	0.143*	1.24	0.18
3		81.4	11.9	0.104	1.52	0.22
4		31.7*	4.6*	0.024*	1.31	0.19
5		89.6	13.2	0.132	1.65	0.24
6		56.0	8.1	0.010*	-	-
average		77.2	11.2	0.101	1.38	0.21
standard deviation		14.5	2.1	0.033	0.14	0.02
LSDC 01	82	44.1*	6.4*	-	-	-
2		81.4	11.8	0.155	1.38	0.20
3		82.0	11.9	0.152	0.90	0.13
4		71.7	10.4	0.128	1.17	0.17
5		62.7	9.1	0.048*	0.69*	0.10*
average		74.5	10.8	0.145	1.17	0.17
standard deviation		8.9	1.3	0.015	0.21	0.03

* Not included in average

TABLE C12

INDIVIDUAL 2220-3 DRY SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSDA 11	23	93.8*	13.6*	0.111*	1.45	0.21
12		91.0	13.2	0.107*	1.45	0.21
13		93.1*	13.5*	0.091	1.46	0.22
14		57.4	8.3	0.053	1.31	0.19
15		57.4	8.3	0.052	1.17	0.17
16		37.2*	5.4*	0.020*	1.86*	0.27*
17		34.5*	5.0*	0.044	0.97*	0.14*
average		68.5	9.9	0.065	1.38	0.20
standard deviation		19.5	2.8	0.020	0.14	0.02
LSDB 11	54	31.0*	4.5*	0.015*	2.41*	0.35*
12		79.5	11.5	0.099	1.17	0.17
14		66.2	9.6	0.154*	-	-
15		75.8	11.0	0.115	1.17	0.17
16		62.7	9.1	0.079	1.38	0.20
average		71.0	10.3	0.098	1.24	0.18
standard deviation		7.8	1.1	0.018	0.14	0.02
LSDC 11	82	57.2	8.3	0.144	1.03	0.15
12		70.3	10.2	0.168*	1.17	0.17
13		60.7	8.8	0.085*	1.10	0.16
14		70.3	10.2	0.142	-	-
15		69.6	10.1	0.099	1.17	0.17
average		66.2	9.6	0.128	1.10	0.16
standard deviation		6.3	0.9	0.025	0.07	0.01

* Not included in average

TABLE C13

INDIVIDUAL 3502 WET SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSWA 31	23	44.8	6.5	0.027	1.72	0.25
32		45.5	6.6	0.026	1.79	0.26
33		53.8	7.8	0.036	0.76*	0.11*
34		55.2	8.0	0.043	1.52	0.22
35		64.1*	9.3*	0.058*	1.31	0.19
average		49.8	7.2	0.033	1.58	0.23
standard deviation		5.4	0.8	0.008	0.21	0.03
LSWB 31	54	46.2	6.7	0.042	1.52	0.22
32		58.6	8.5	0.052	1.03*	0.15*
33		51.0	7.4	0.051	1.31	0.19
34		57.9	8.4	0.046	1.31	0.19
35		27.6*	4.0*	0.022*	1.24	0.18
36		57.2	8.3	0.047	1.52	0.22
average		54.5	7.9	0.048	1.38	0.20
standard deviation		5.4	0.8	0.004	0.14	0.02
LSWC 31	82	59.3*	8.6*	0.076*	1.03	0.15
32		44.1	6.4	0.054	0.69	0.10
33		49.6	7.2	0.052	1.03	0.15
34		42.7	6.2	0.030	2.21*	0.32*
35		17.2*	2.5*	0.015*	1.24	0.18
average		45.5	6.6	0.045	0.97	0.14
standard deviation		3.7	0.5	0.013	0.21	0.03

* Not included in average

TABLE C14

INDIVIDUAL FIBREDUX 914 WET SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSWA 21	23	87.0	11.9	0.092	1.38	0.20
22		28.3*	4.1*	0.014*	1.72*	0.25*
23		78.6	11.4	0.106*	1.52	0.22
24		59.3	8.6	0.044	1.38	0.20
25		56.5	8.2	0.054	1.03*	0.15*
average		68.9	10.0	0.063	1.45	0.21
standard deviation		13.1	1.9	0.025	0.07	0.01
LSWB 21	54	40.0	5.8	0.032	1.03	0.15
22		45.5	6.6	0.041	1.31	0.19
23		40.7	5.9	0.036	1.24	0.18
24		44.8	6.5	0.031	1.93*	0.28*
25		41.4	6.0	0.034	1.31	0.19
average		42.7	6.2	0.035	1.24	0.18
standard deviation		2.7	0.4	0.004	0.14	0.02
LSWC 21	82	38.6	5.6	0.043	1.10	0.16
22		44.8	6.5	0.064	1.17	0.17
23		54.5*	7.9*	0.040	1.24	0.18
24		33.1	4.8	0.032	1.24	0.18
25		28.3*	4.1*	0.098*	1.10	0.16
average		38.6	5.6	0.045	1.17	0.17
standard deviation		5.9	0.9	0.010	0.70	0.01

* Not included in average

TABLE C15

INDIVIDUAL 2220-1 WET SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSWA 01	23	66.9	9.7	0.070	1.38	0.20
2		78.6	11.4	0.114	1.38	0.20
3		60.0	8 7	0.052	1.72	0.25
4		42.7	6.2*	0.032	1.59	0.23
5		68.3	9.9	-	-	-
6		84.8*	12.3*	0.174*	1.52	0.22
average		68.2	9.9	0.067	1.52	0.22
standard deviation		7.6	1.1	0.035	0.14	0.02
LSWB 01	54	68.3	9.9	0.021*	1.24	0.18
2		67.6	9.8	0.155	1.10*	0.16*
3		69.6	10.1	0.152	1.38	0.20
4		64.8	9.4	0.128	1.24	0.20
5		59.3	8.6	0.049	1.24	0.18
average		66.2	9.6	0.121	1.31	0.19
standard deviation		4.3	0.6	0.049	0.07	0.01
LSWC 01	82	56.5	8.2	0.062	1.10	0.16
2		51.7	7.5	0.090	1.45	0.21
3		57.9	8.4	0.094	1.38	0.20
4		53.8	7.8	0.105	1.03	0.15
5		54.5	7.9	0.089	1.10	0.16
average		55.2	8.0	0.095	1.24	0.18
standard deviation		2.5	0.4	0.007	0.21	0.03

* Not included in average

TABLE C16

INDIVIDUAL 2220-3 WET SHEAR RESULTS

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain	Modulus (GPa)	Modulus (Msi)
LSWA 11	23	71.0	10.3	0.089*	1.65	0.24
12		71.0	10.3	0.123	1.45	0.21
13		78.6	11.4	0.141	1.38	0.20
14		81.4	11.8	0.170*	0.69*	0.10*
15		79.3	11.5	0.130	0.76*	0.11*
average		75.8	11.1	0.131	1.17	0.22
standard deviation		4.7	0.7	0.009	0.38	0.02
LSWB 11	54	63.4	9.2	0.120	1.17	0.17
12		65.5	9.5	0.159	1.38	0.20
13		65.5	9.5	0.140	1.24	0.18
14		53.8	7.8	0.059*	1.38	0.20
15		66.9	9.7	0.158	1.10	0.16
average		62.7	9.1	0.144	1.24	0.18
standard deviation		5.4	0.8	0.018	0.14	0.02
LSWC 11	82	53.8	7.8	0.055*	1.38	0.20
12		49.0	7.1	0.098	0.69*	0.10*
13		46.2	6.7	0.124	1.31	0.19
14		49.0	7.1	0.137	1.31	0.19
15		49.0	7.1	0.153	1.31	0.19
average		49.6	7.2	0.128	1.31	0.19
standard deviation		2.7	0.4	0.023	0.03	0.01

* Not included in average

TABLE C17

COEFFICIENTS OF THERMAL EXPANSION OF THE

VARIOUS EPOXY MATRIX MATERIALS

Resin System	Temp (°C)	Dry Condition (10^{-6} in/in-°C)	Moisture-Saturated Condition (10^{-6} in/in-°C)
3502	23	37.4	54.6
	54	44.1	61.3
	82	54.2	58.8
	93	59.3	55.6
914	23	65.9	58.0
	54	77.5	57.8
	82	96.8	58.7
	93	106.7	59.3
2220-1	23	59.4	59.9
	54	56.3	64.0
	82	59.2	55.1
	93	61.8	48.3
2220-3	23	48.2	61.2
	54	55.5	68.3
	82	56.8	66.5
	93	56.0	63.6

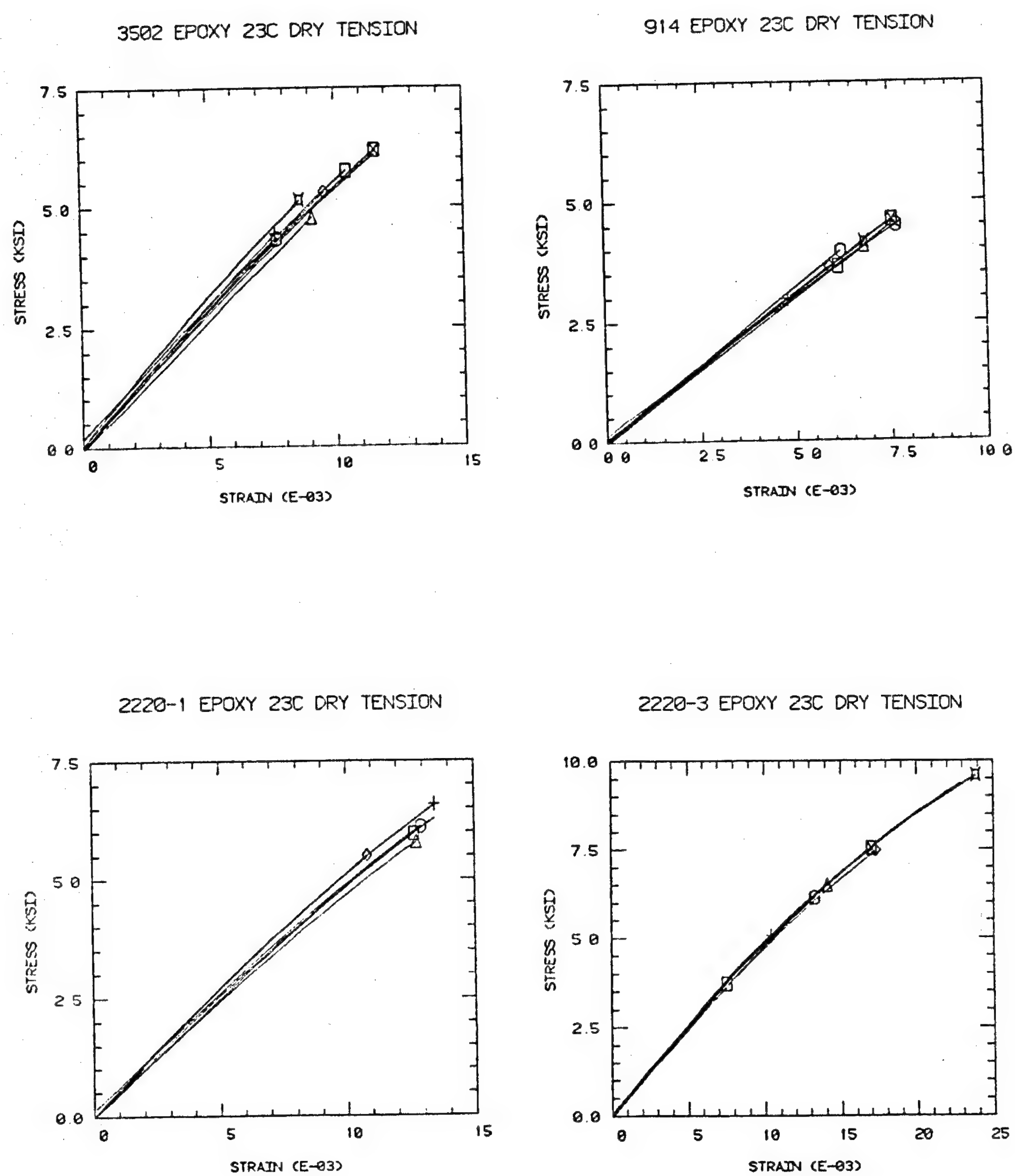


Figure C1. Tensile Stress-Strain Curves, 23°C, Dry.

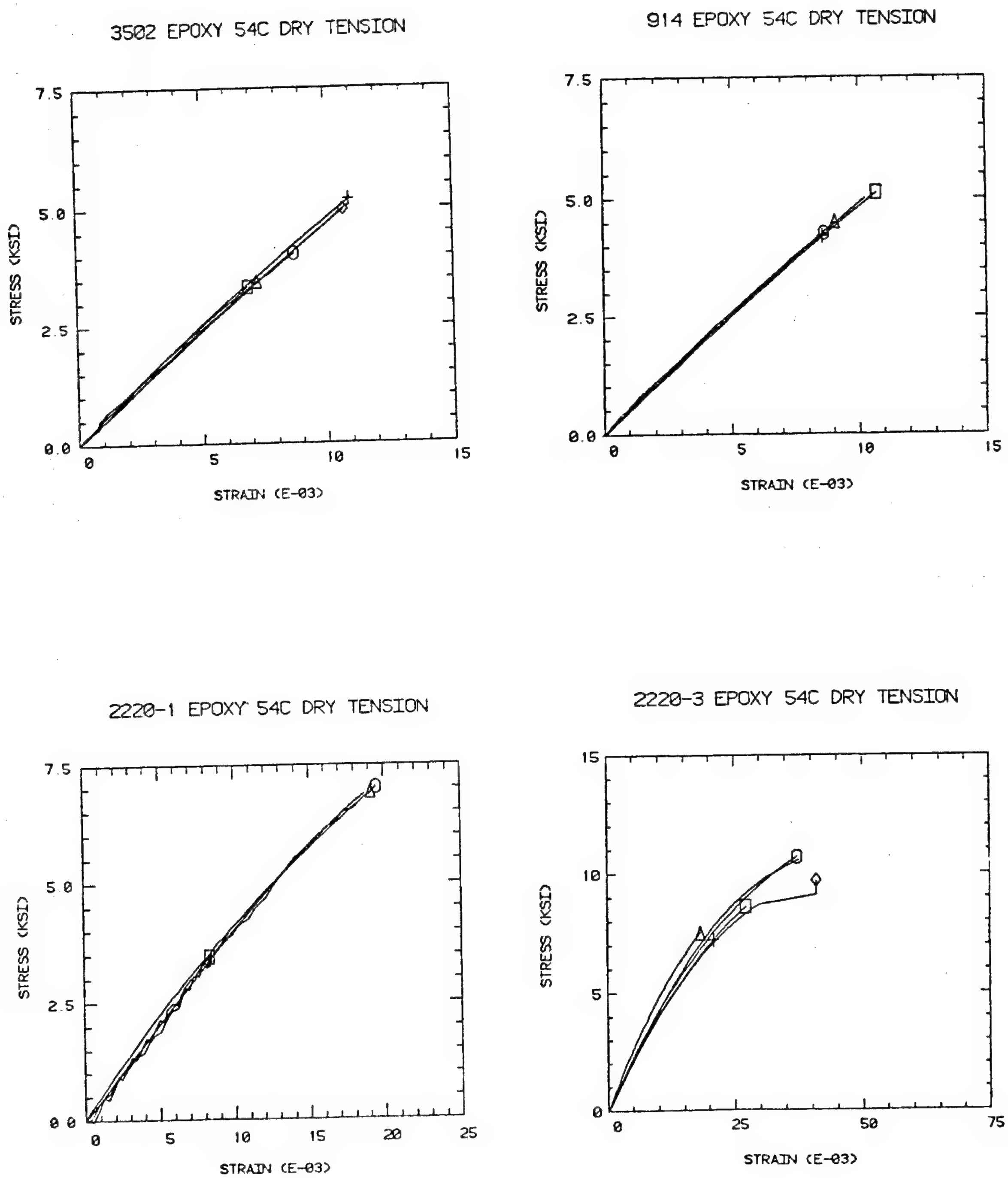


Figure C2. Tensile Stress-Strain Curves, 54°C, Dry.

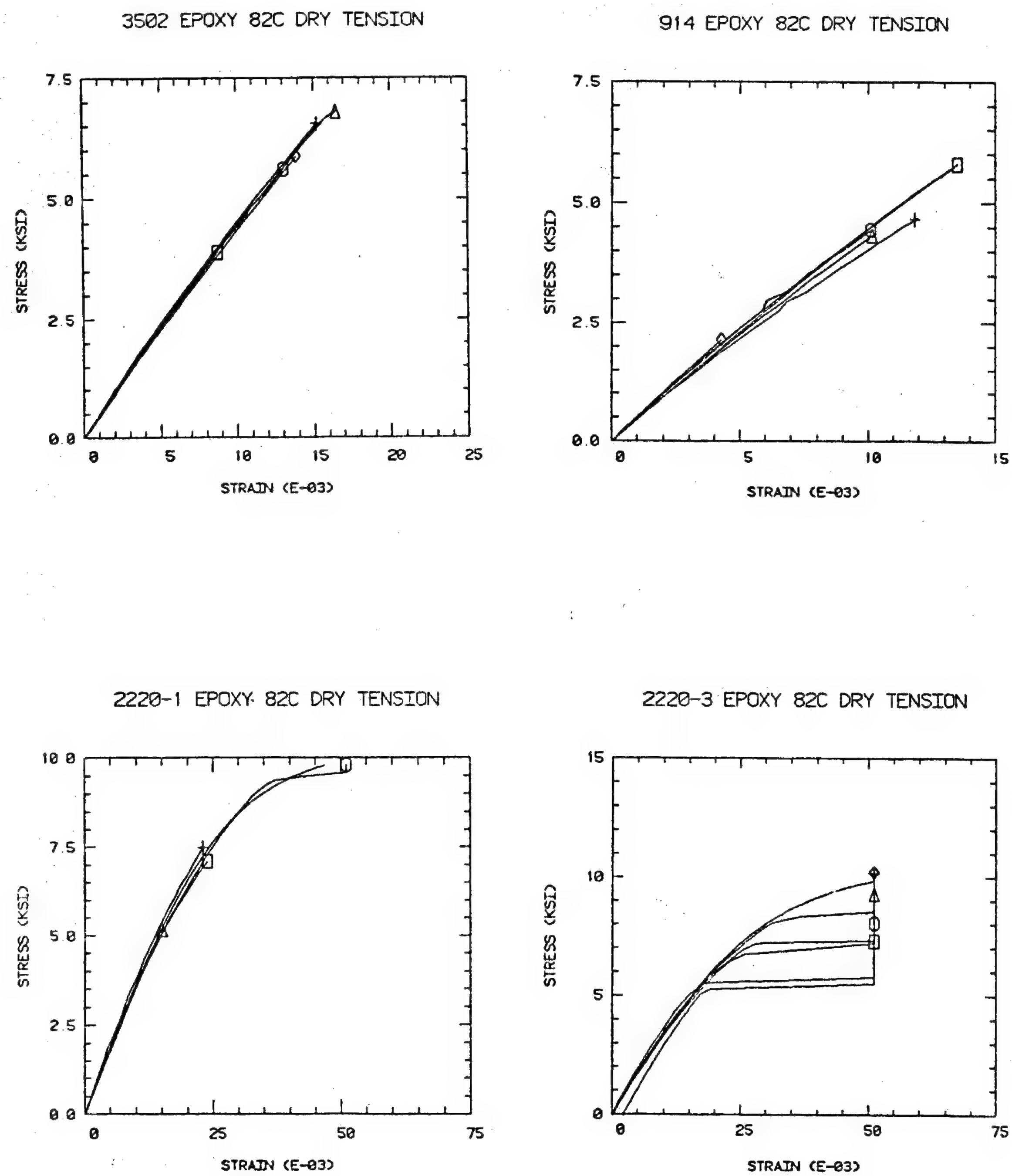


Figure C3. Tensile Stress-Strain Curves, 82°C, Dry.

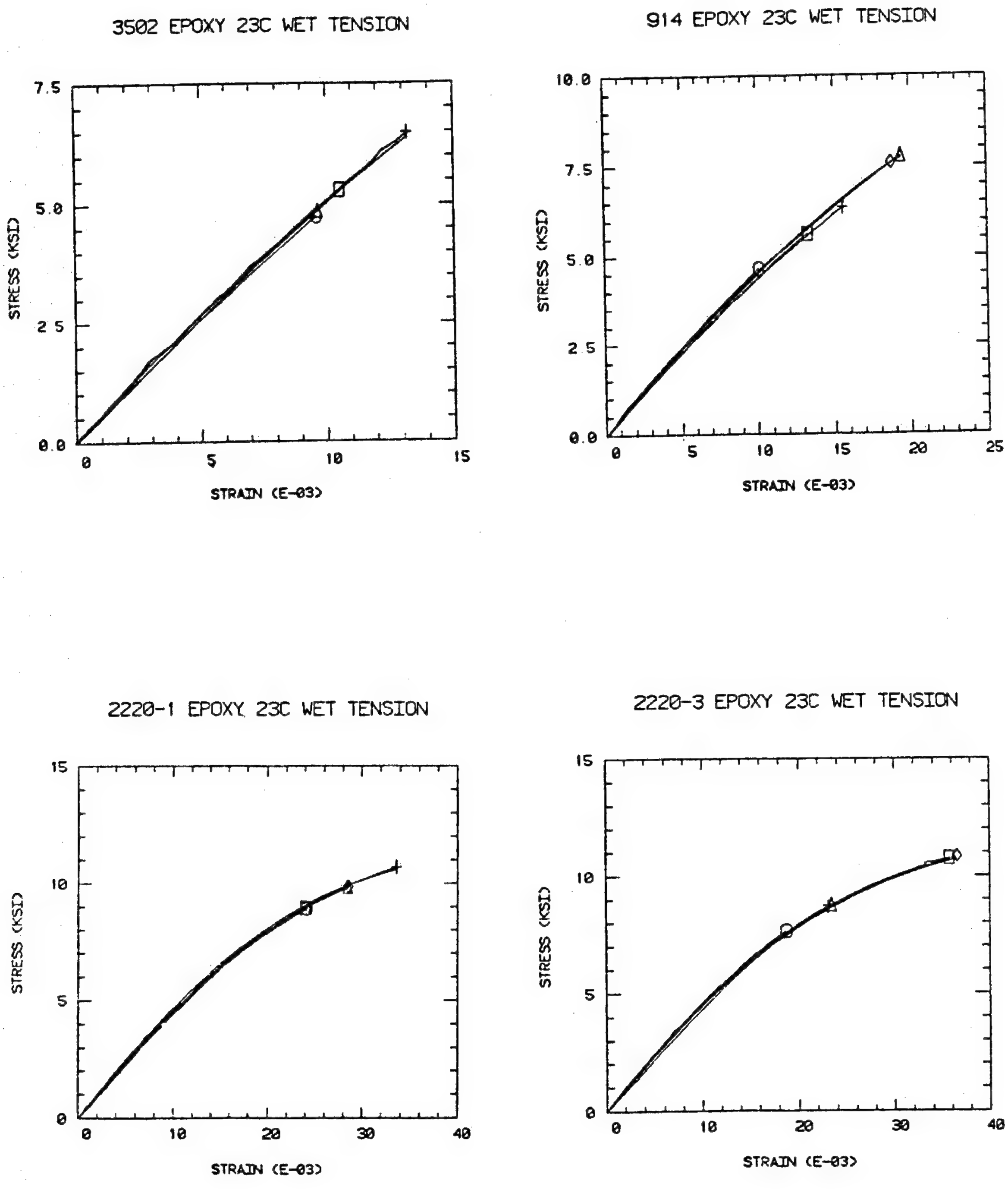


Figure C4. Tensile Stress-Strain Curves, 23°C, Wet.

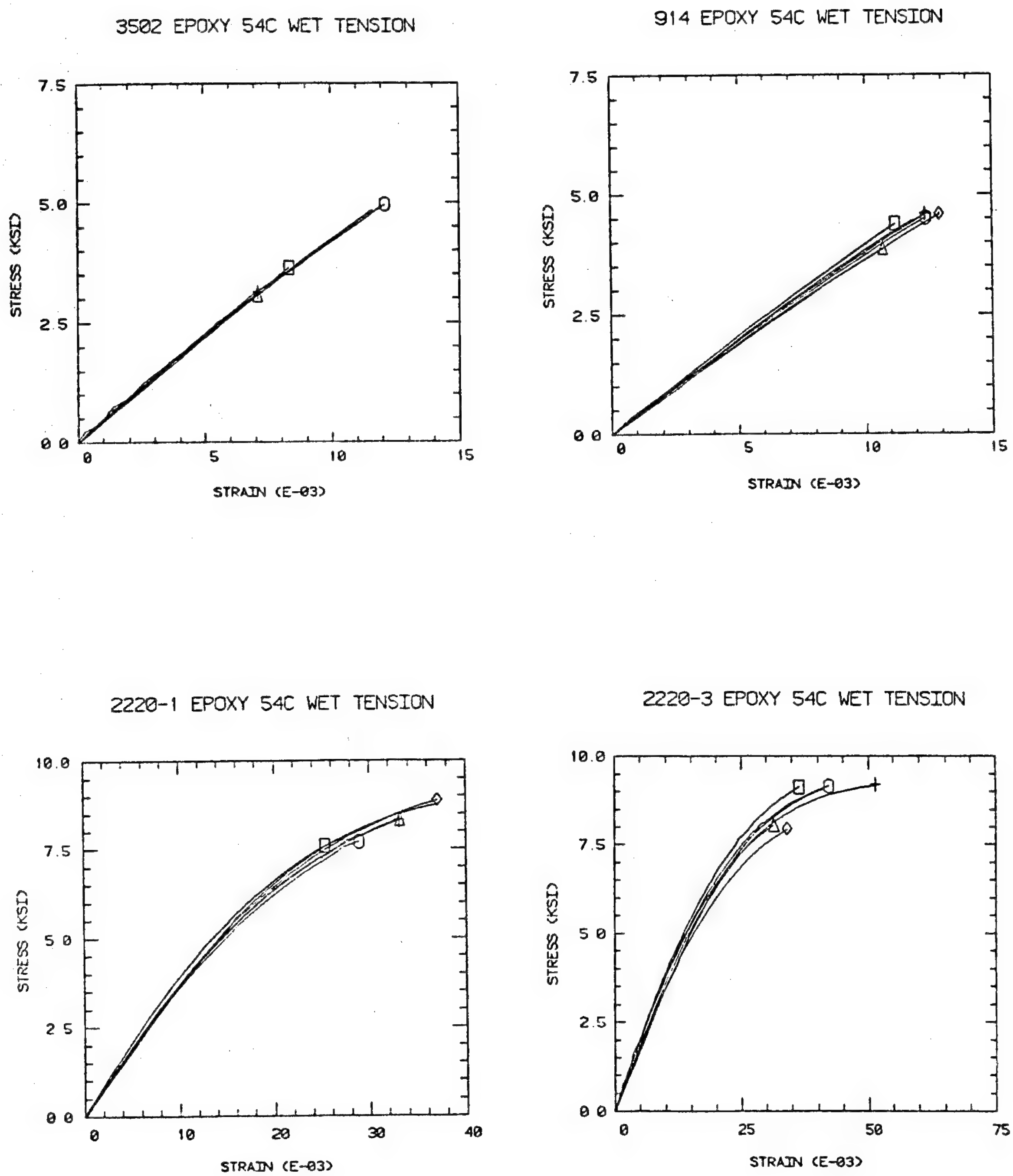


Figure C5. Tensile Stress-Strain Curves, 54°C, Wet.

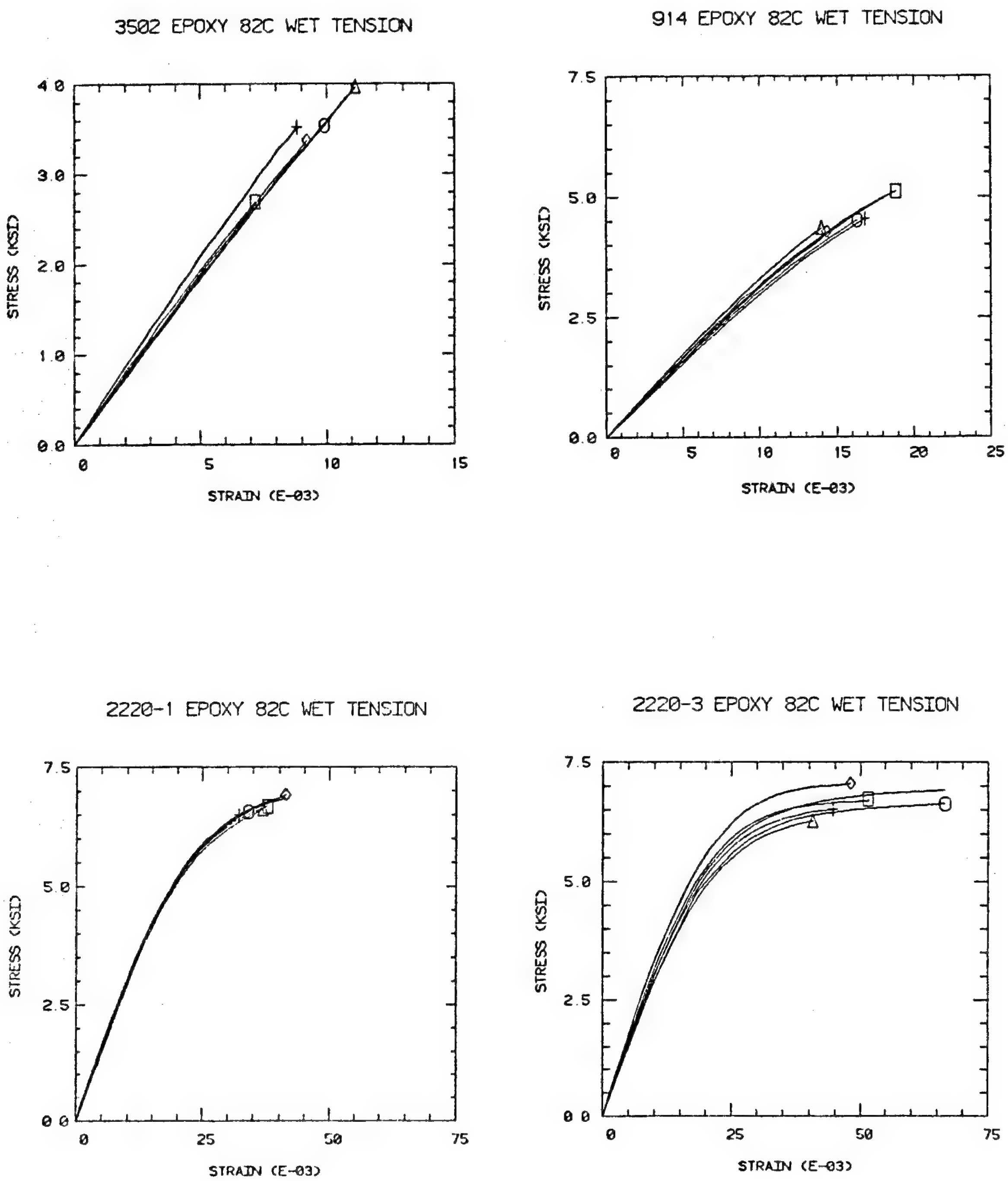


Figure C6. Tensile Stress-Strain Curves, 82°C, Wet.

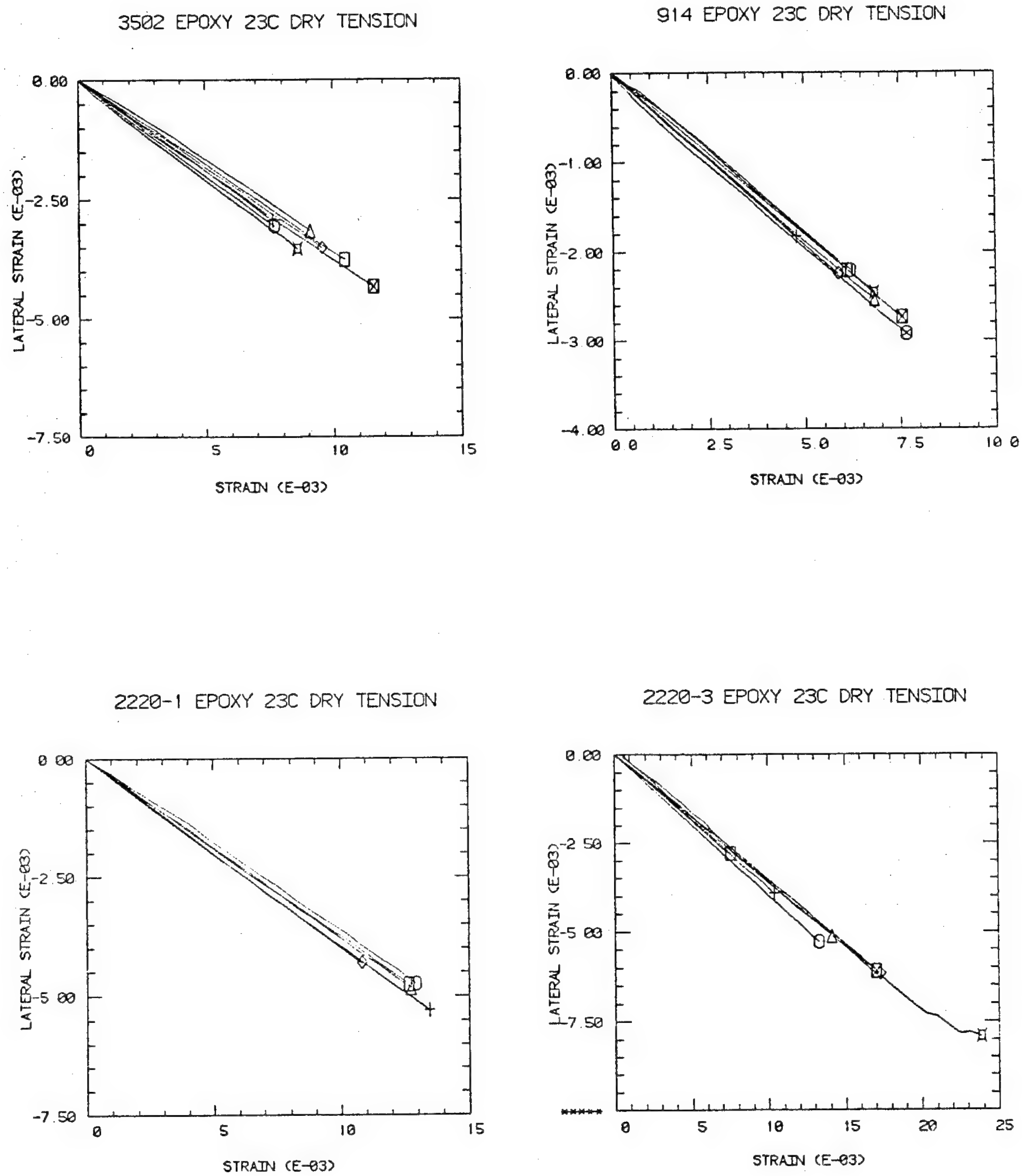


Figure C7. Poisson's Ratio Curves, 23°C, Dry.

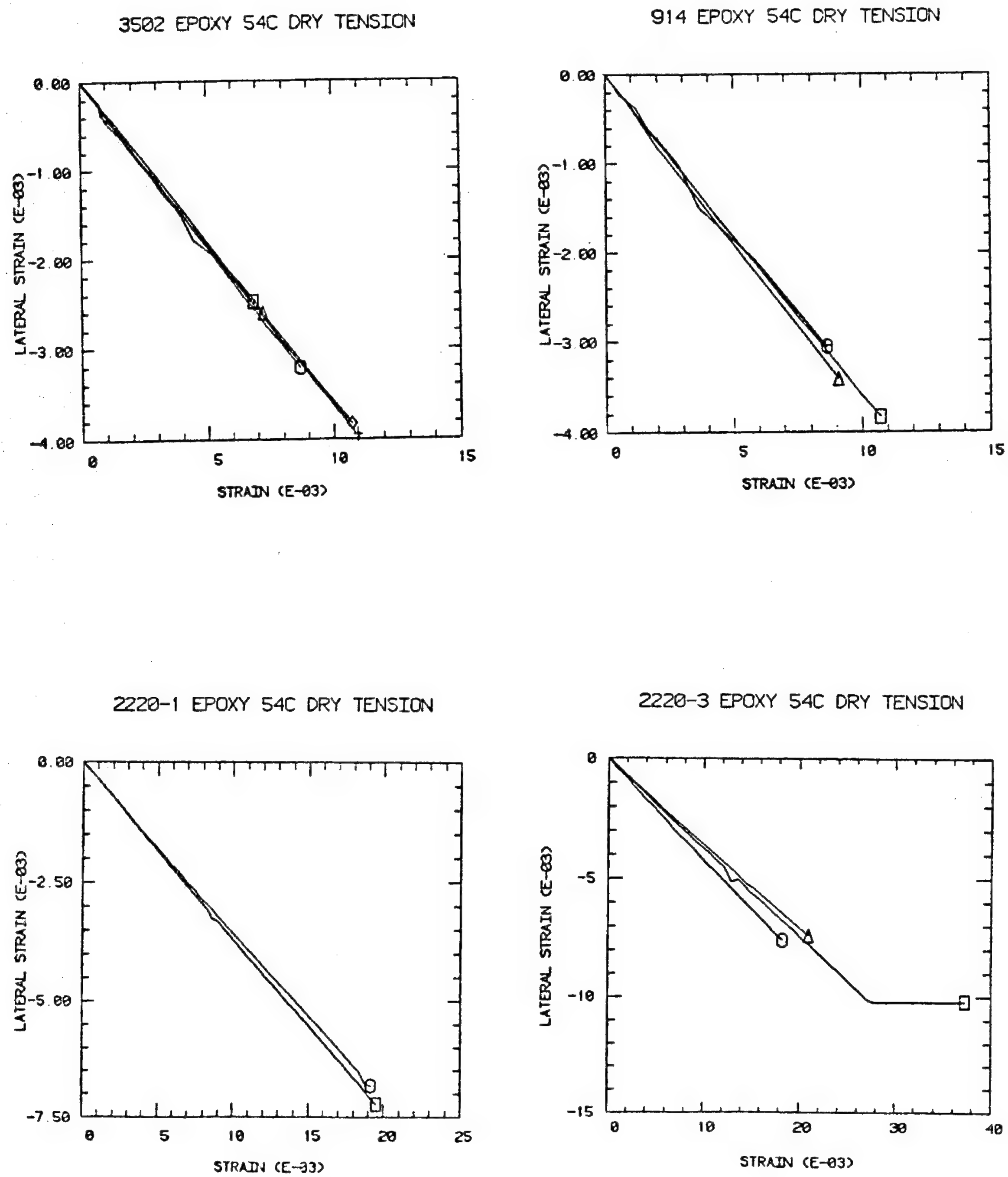


Figure C8. Poisson's Ratio Curves, 54°C, Dry.

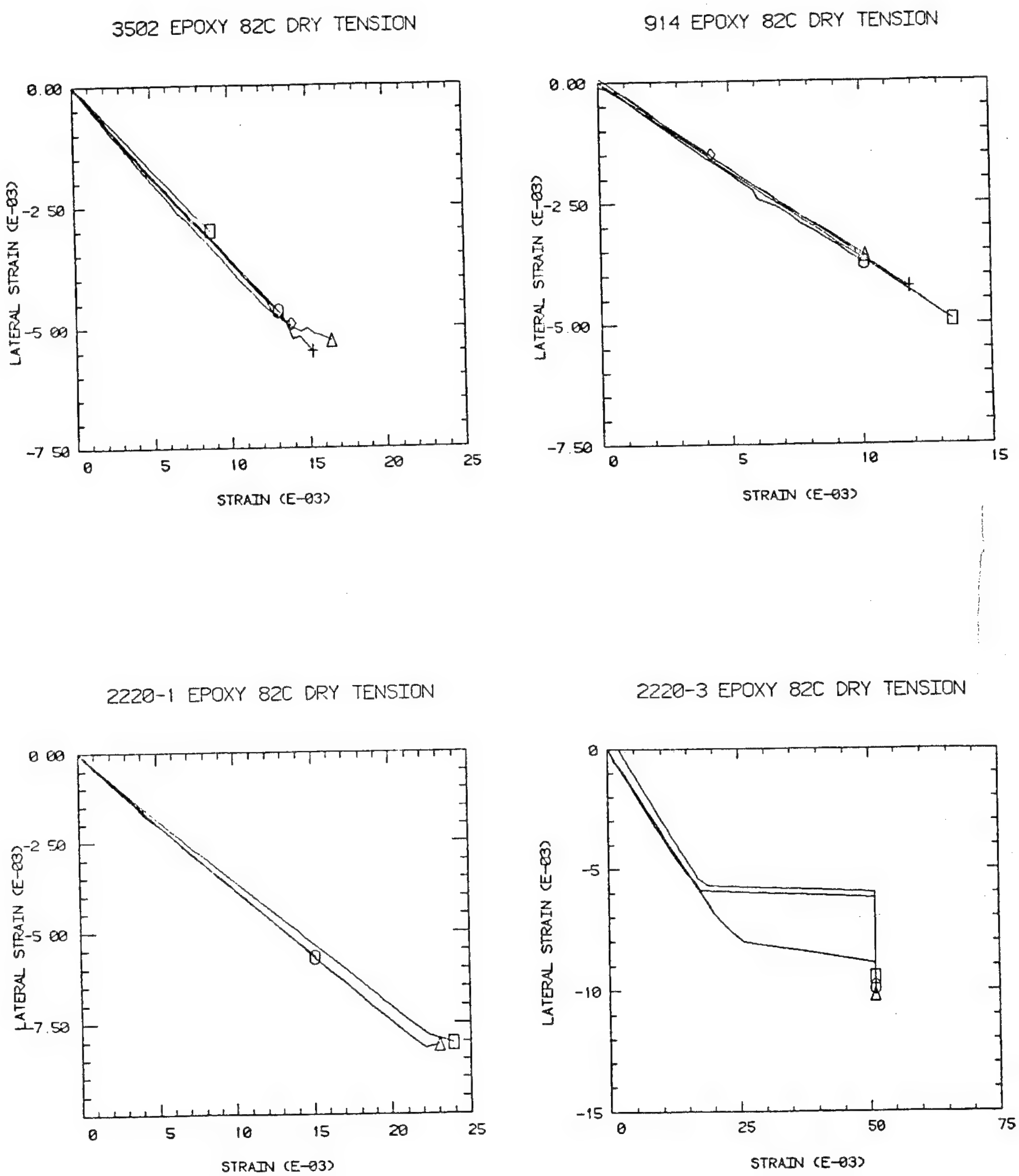


Figure C9. Poisson's Ratio Curves, 82°C, Dry.

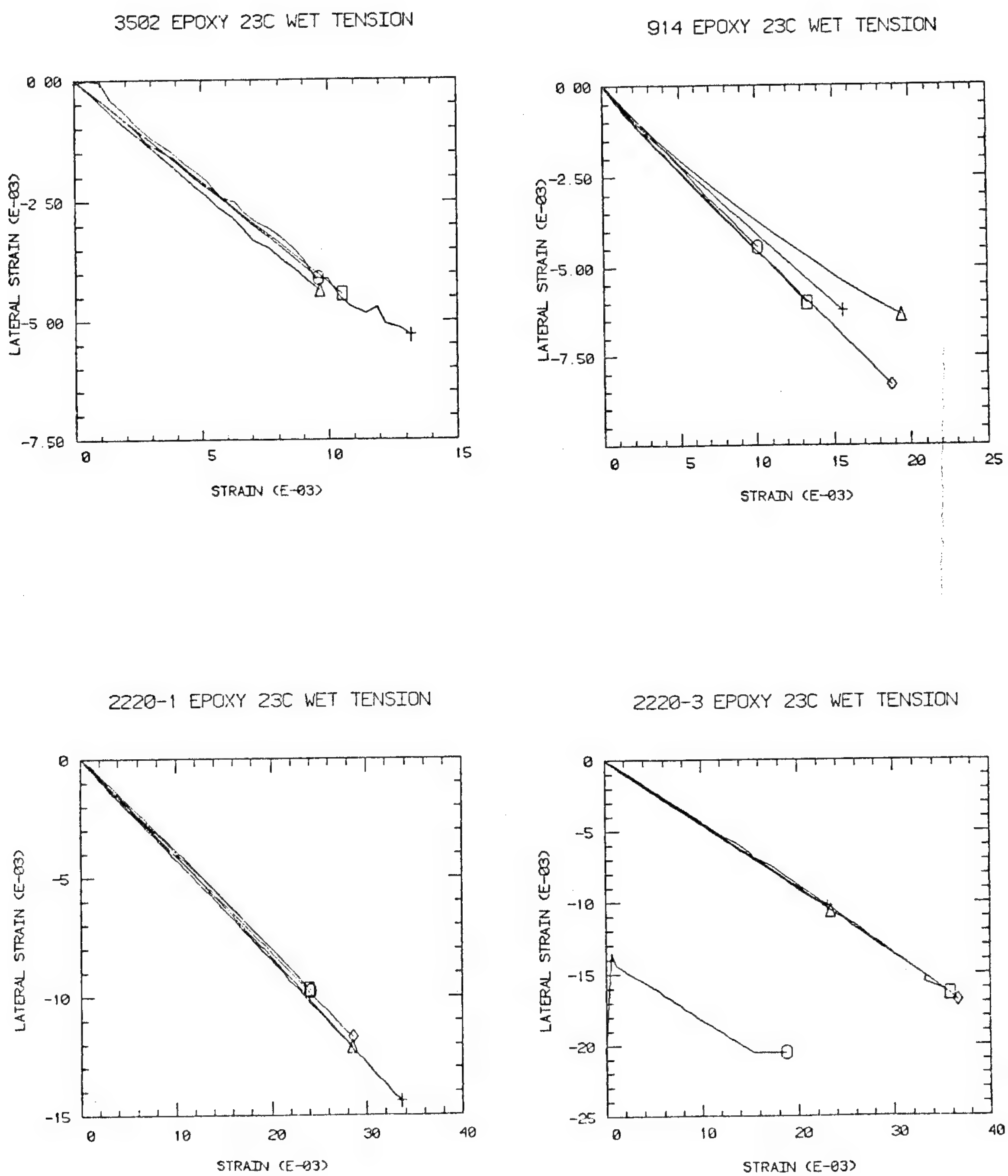


Figure C10. Poisson's Ratio Curves, 23°C, Wet.

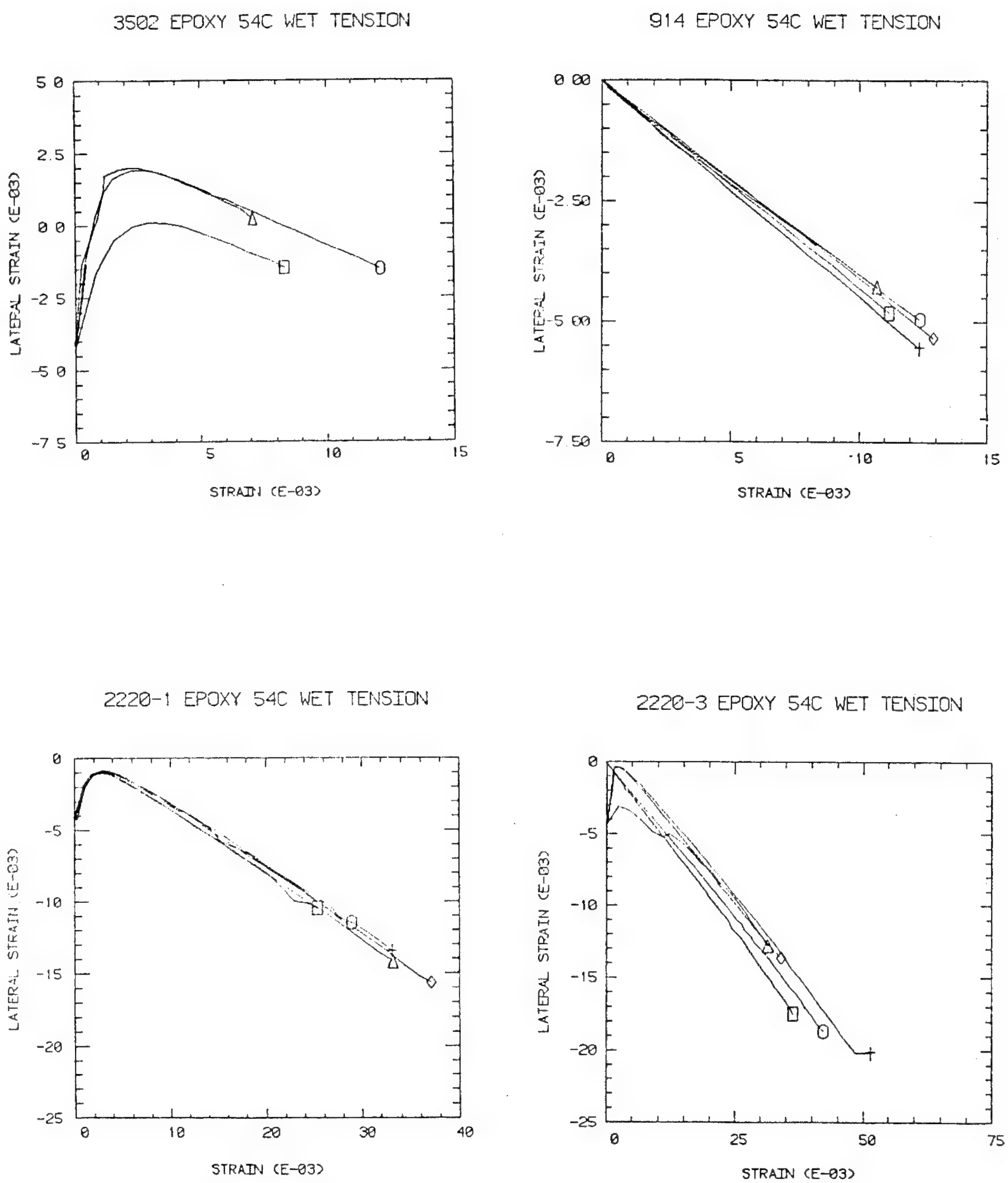


Figure C11. Poisson's Ratio Curves, 54°C, Wet.

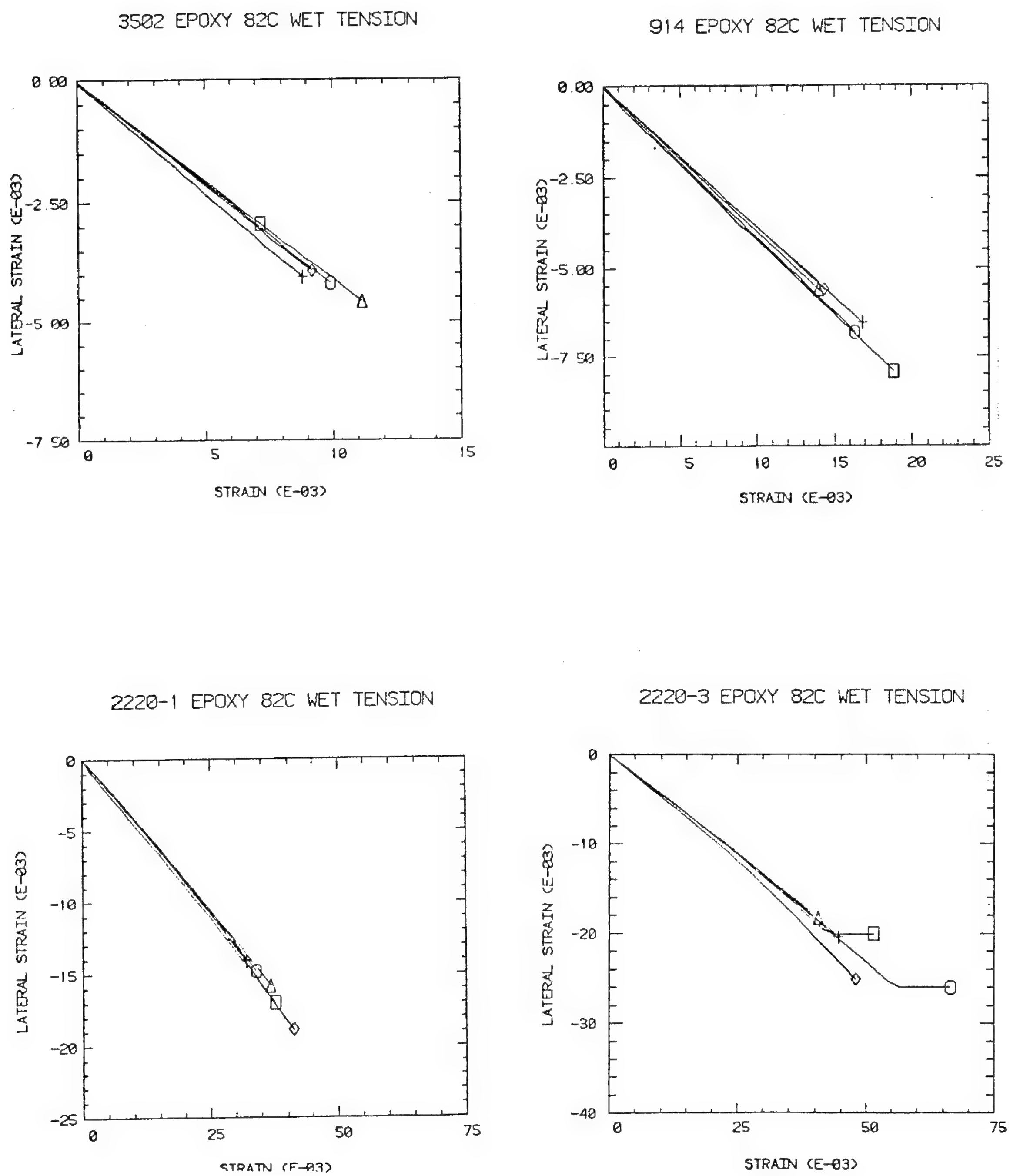


Figure C12. Poisson's Ratio Curves, 82°C, Wet.

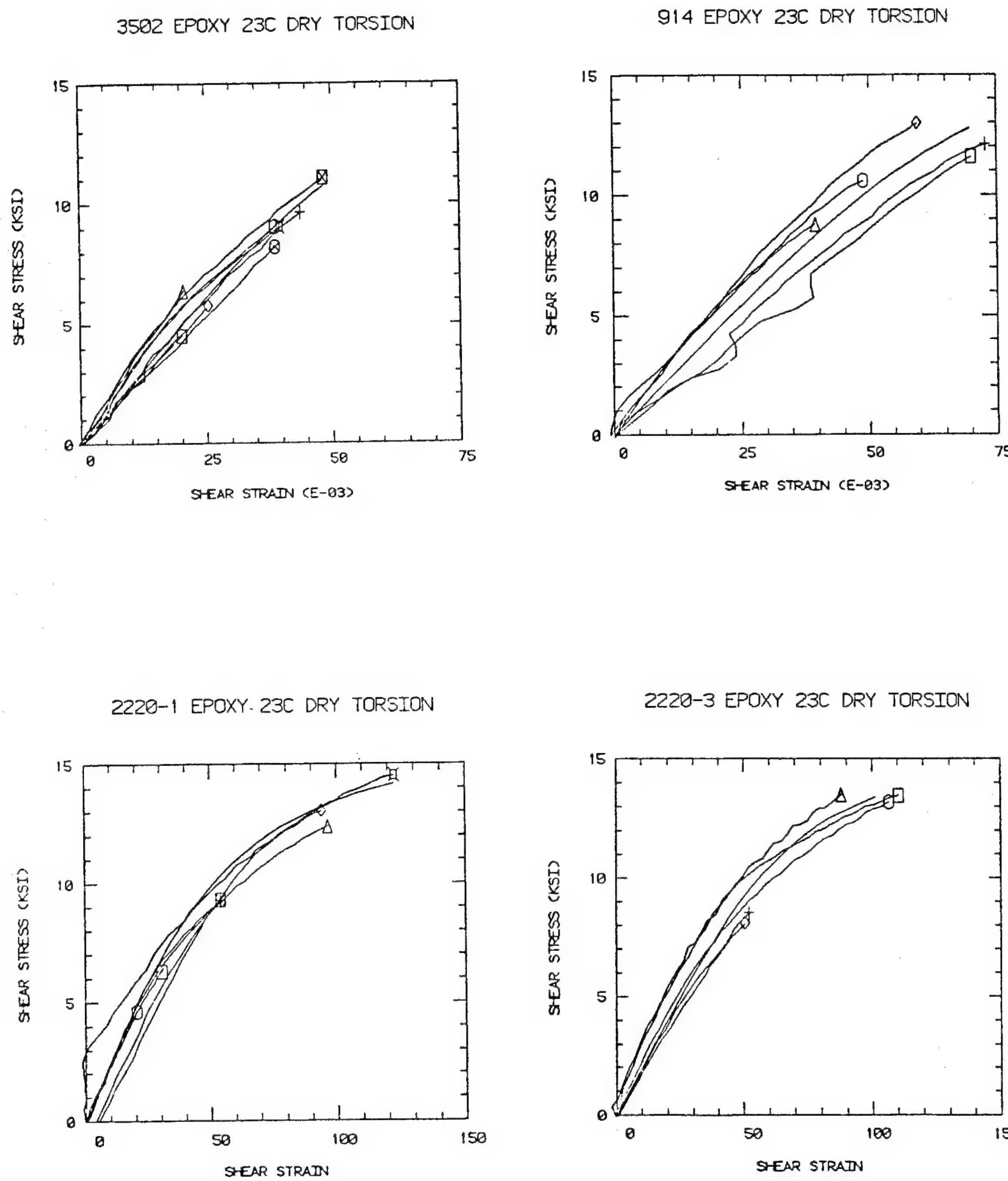


Figure C13. Shear Stress Strain Curves, 23°C, Dry.

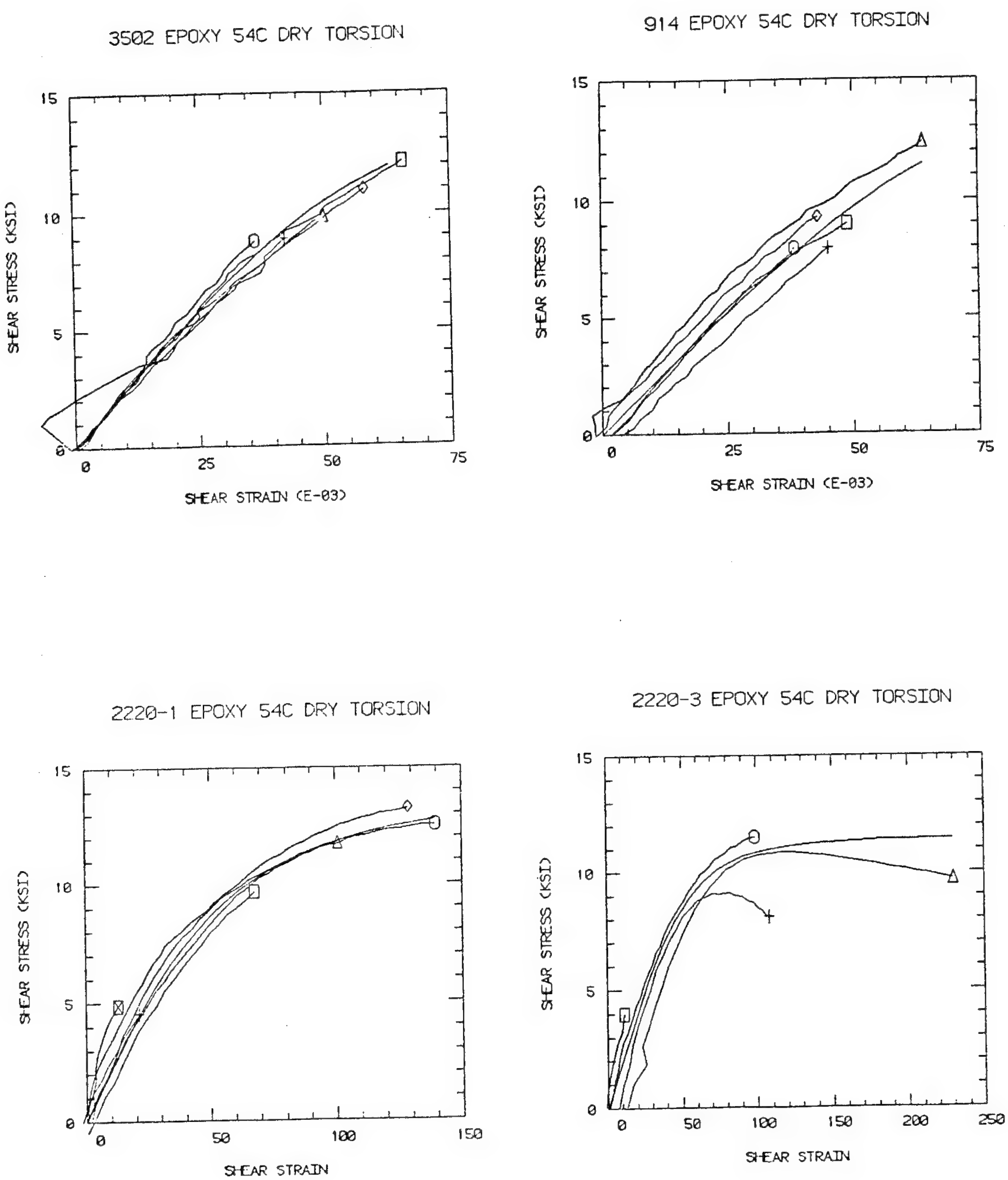


Figure C14. Shear Stress Strain Curves, 54°C, Dry.

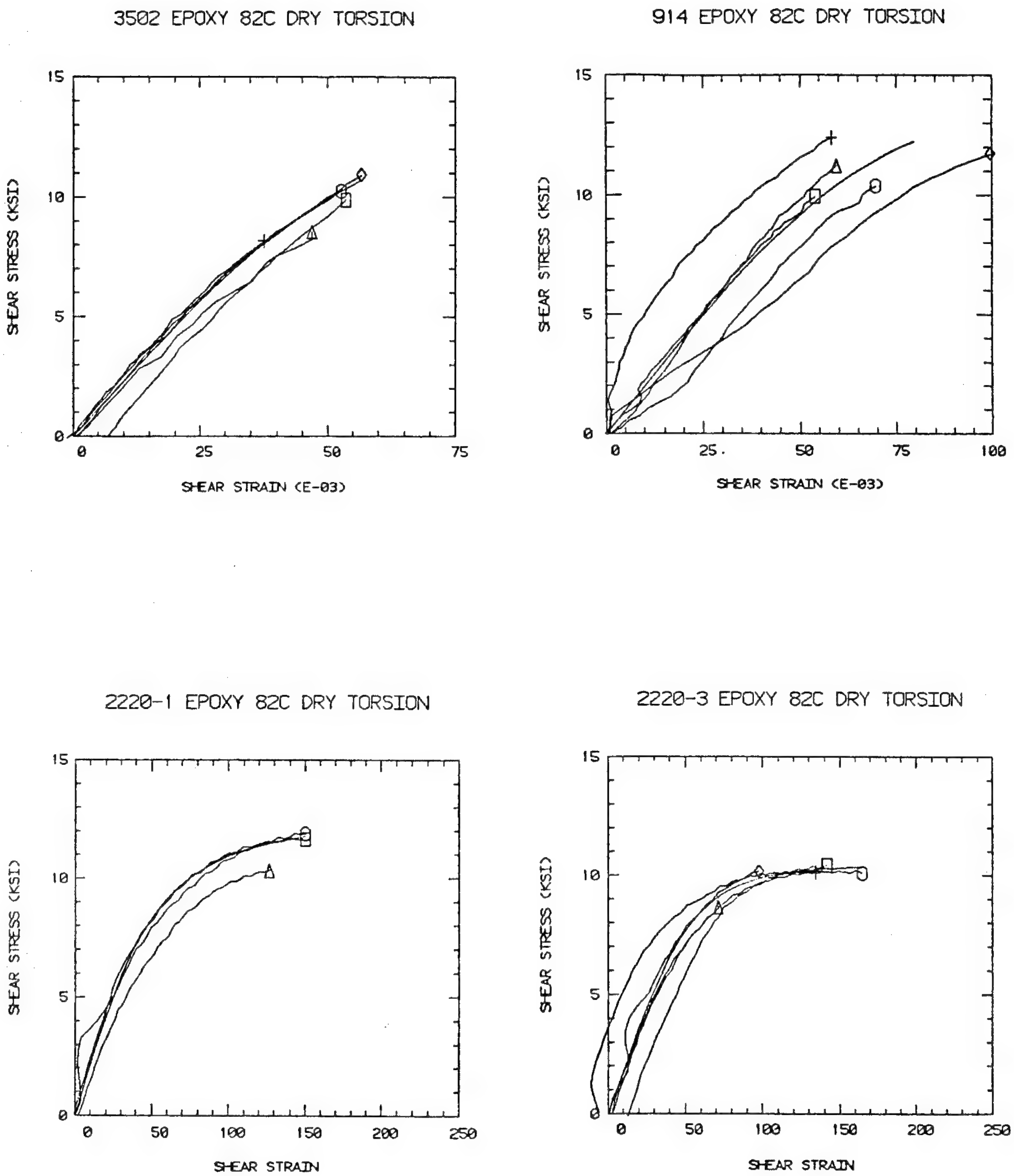


Figure C15. Shear Stress Strain Curves, 82°C, Dry.

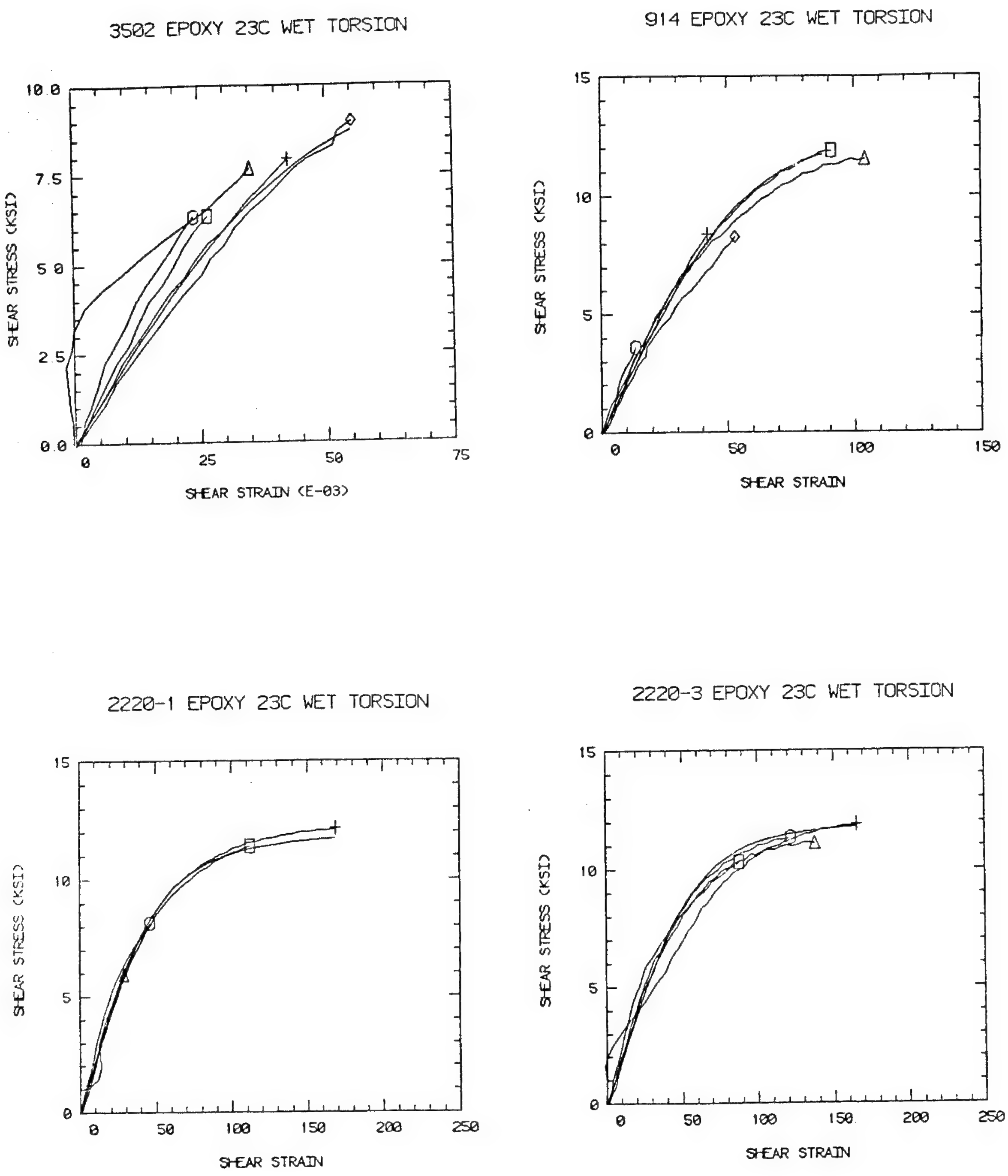


Figure C16. Shear Stress Strain Curves, 23°C, Wet.

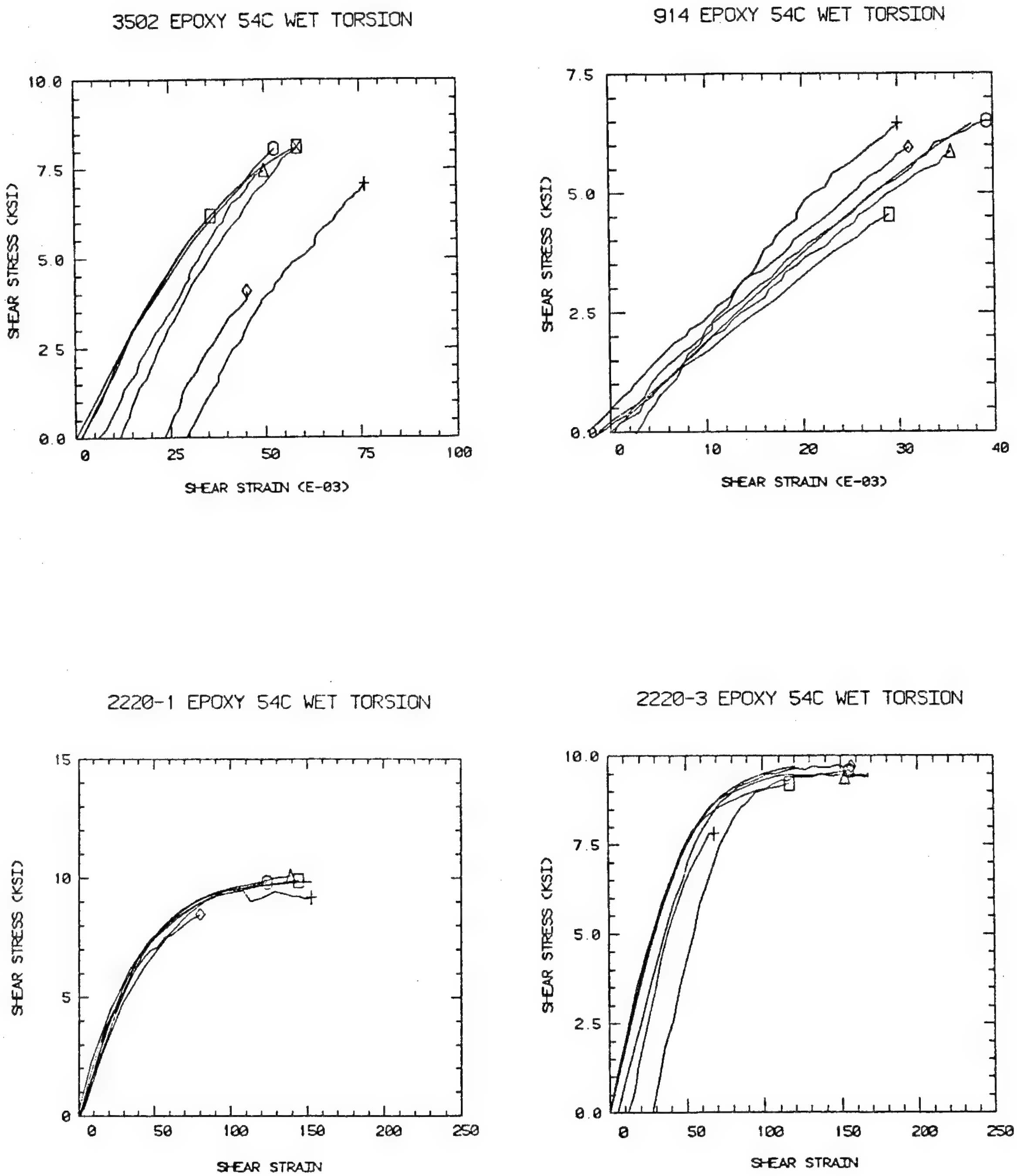


Figure C17. Shear Stress Strain Curves, 54°C, Wet.

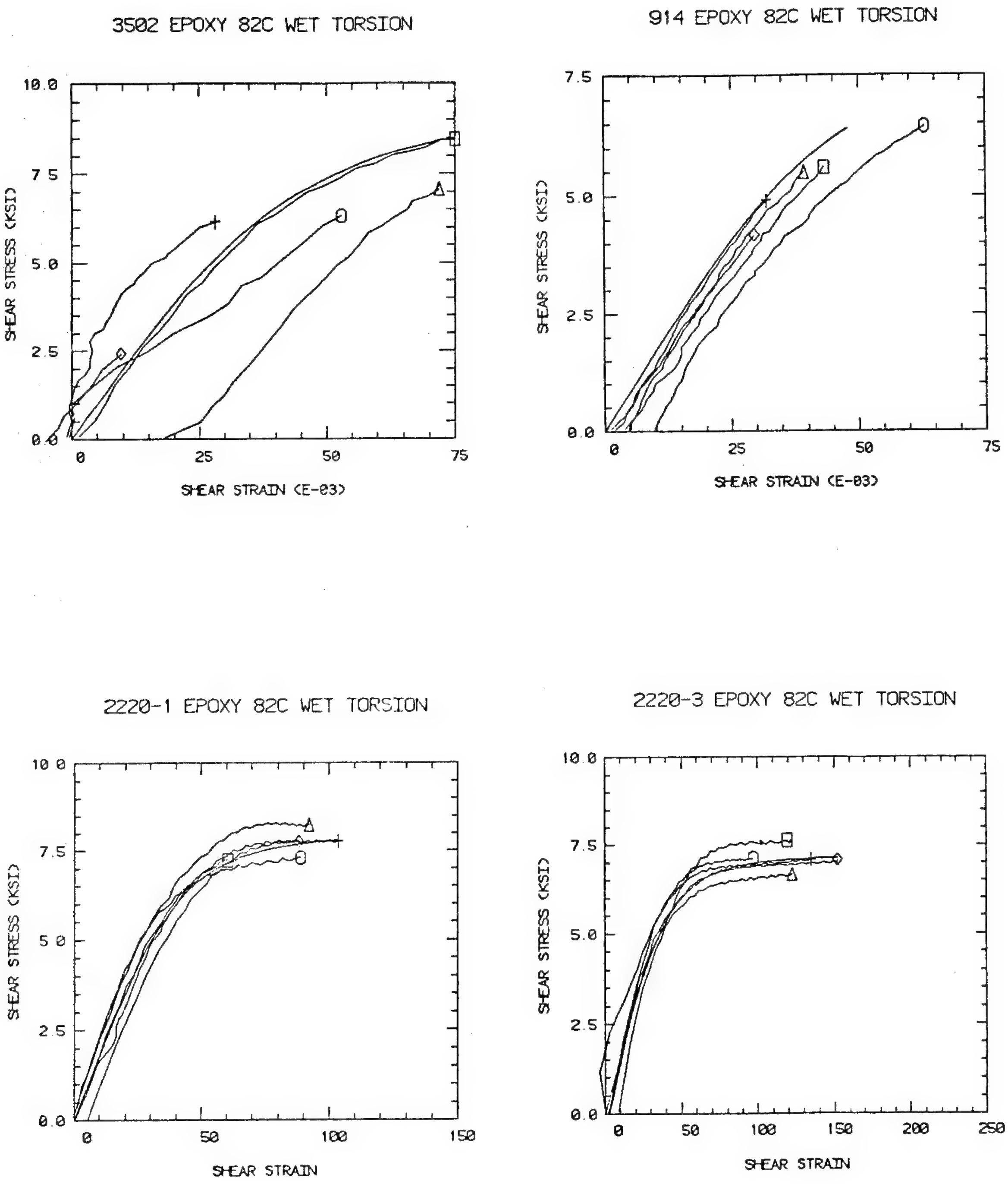


Figure C18. Shear Stress Strain Curves, 82°C, Wet.

APPENDIX D

ADDITIONAL SEM FRACTURE SURFACE PHOTOGRAPHS

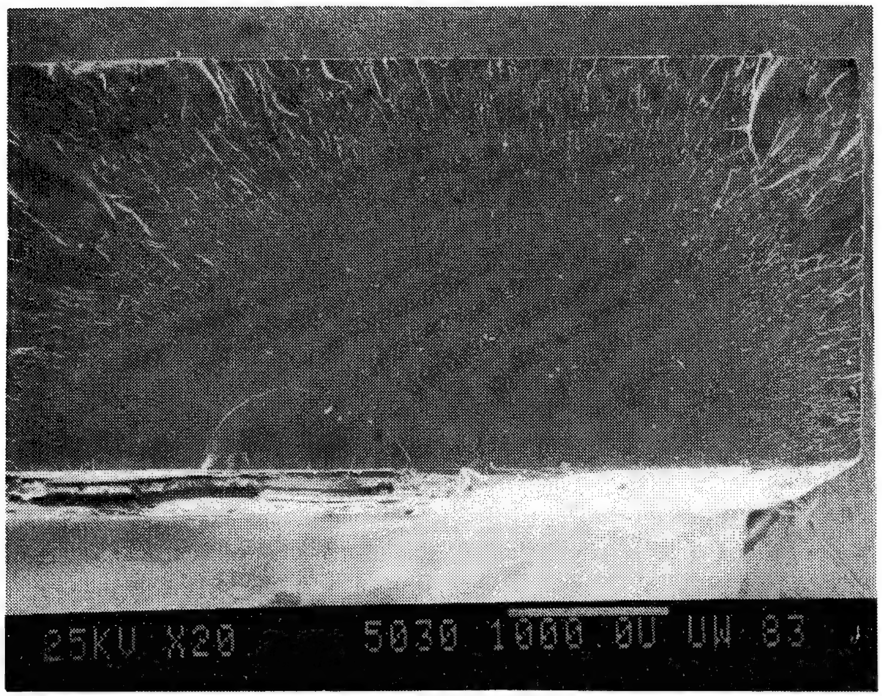


Figure D1. 3502 Neat Epoxy Tension, Specimen No. LTDA35, 23°C, Dry.

A large smooth region surrounded by a minimal coarse area is shown in this photograph. The triangular chip region typically observed in the gross failure observations is off the picture to the left. No explicit initiation site was discernible on the surface but is assumed to have been somewhere in the smooth region.

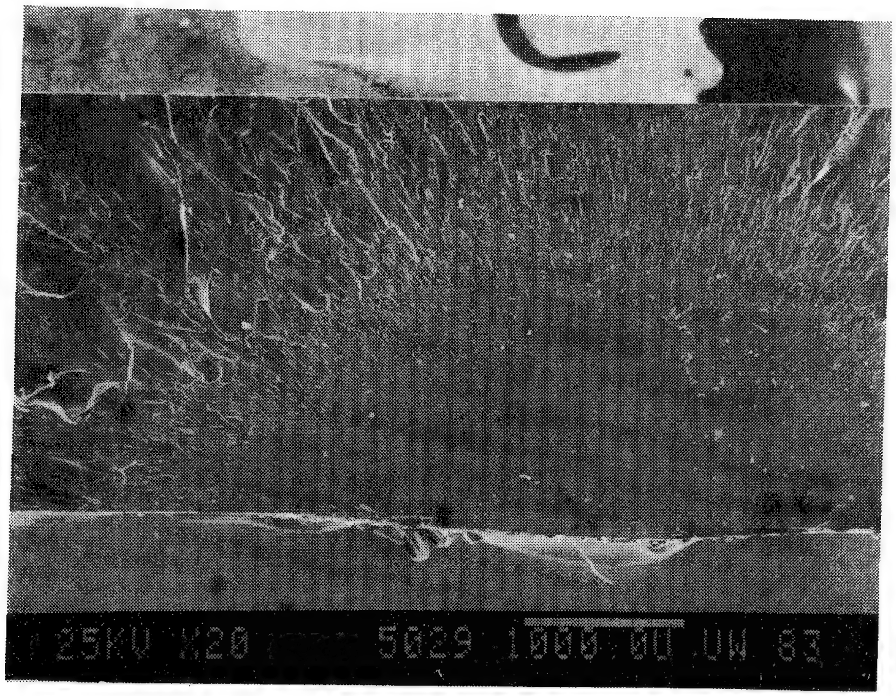


Figure D2. 3502 Neat Epoxy Tension, Specimen No. LTDB34, 54°C, Dry.

A smaller smooth region is typical for this test condition than at room temperature (23°C), dry or wet. The rough area is similar in appearance, however.

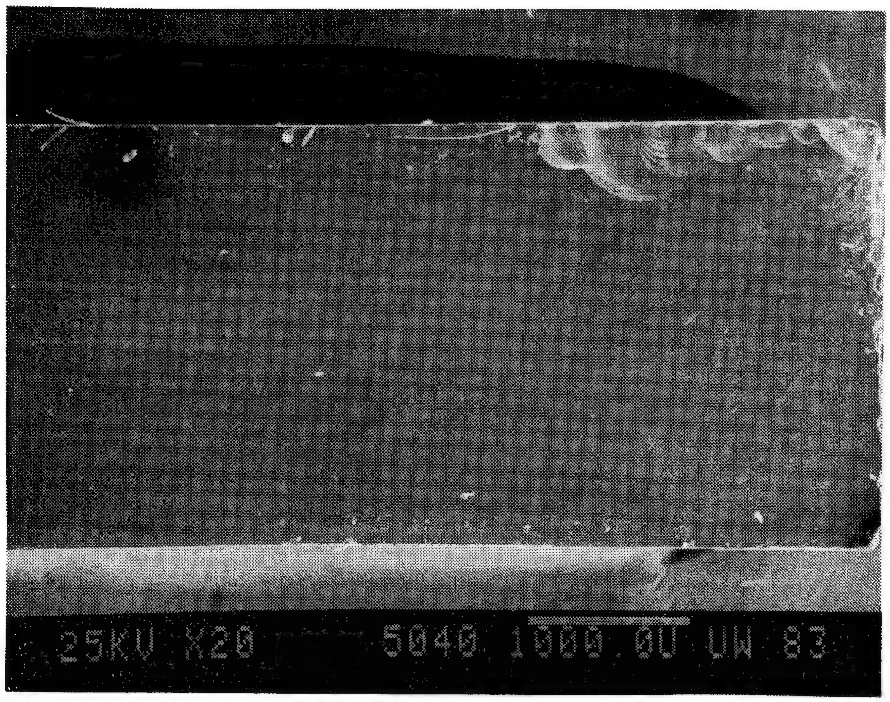


Figure D3. 3502 Neat Epoxy Tension, Specimen No. LTWB34, 54°C, Moisture-Saturated.

This failure is quite unique showing a very smooth glassy appearance over the entire surface. A relatively low strength was recorded for this specimen. The small clamshell marks at the top right edge of the specimen could possibly be where the failure initiated.

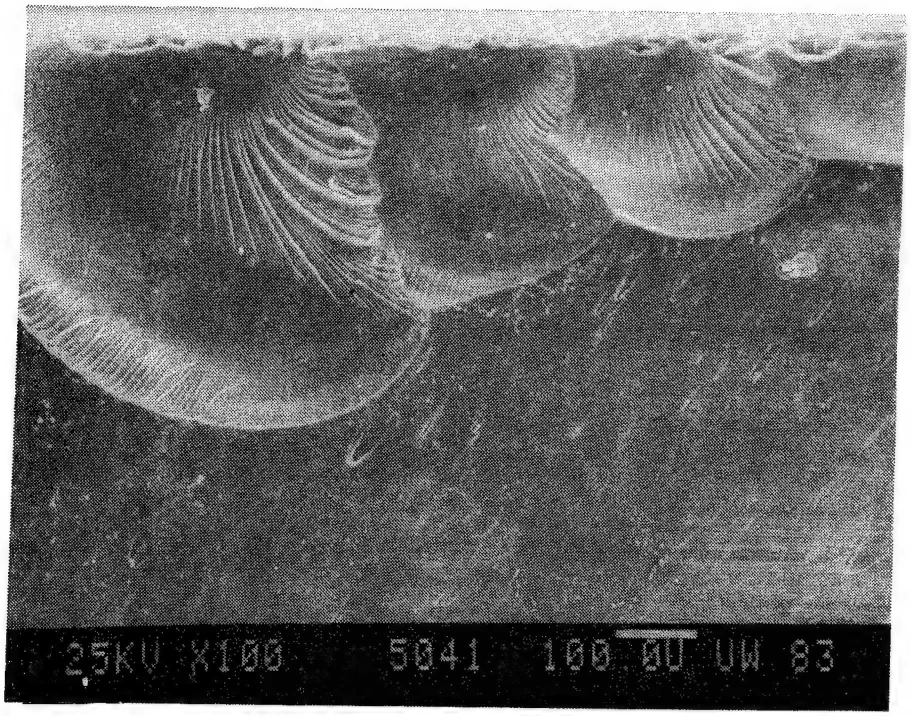


Figure D4. 3502 Neat Epoxy Tension, Specimen No. LTWB34, 54°C, Moisture-Saturated.

This is a higher magnification view of a local region of Figure D3 showing the clamshell marks.

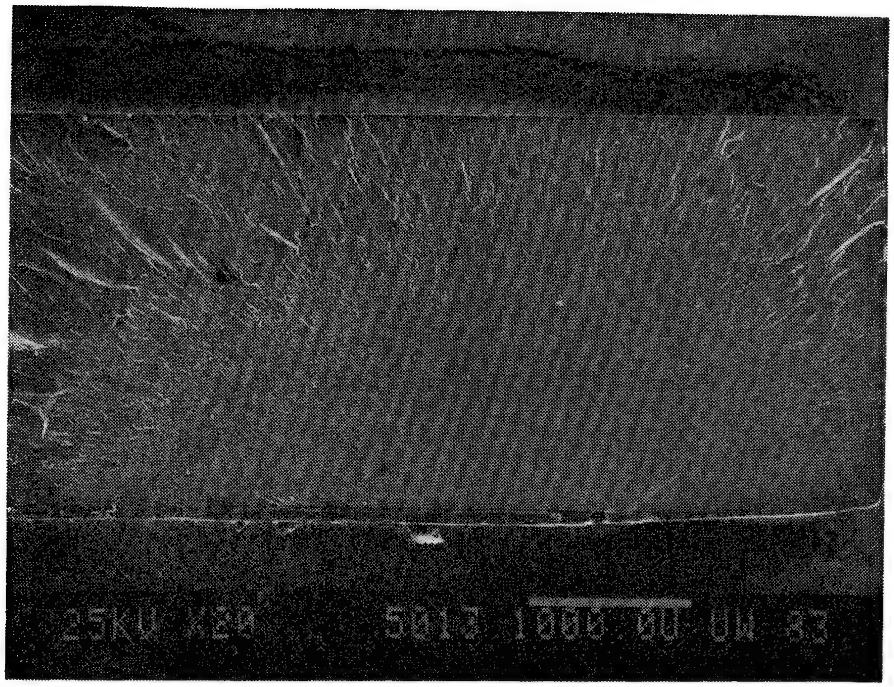


Figure D5. Fibredux 914 Neat Epoxy Tension, Specimen No. LTDA23, 23°C, Dry.

There are no distinguishing characteristics in this typical photograph of 914 epoxy to differentiate it from the 3502 epoxy fractures observed at the same test conditions.

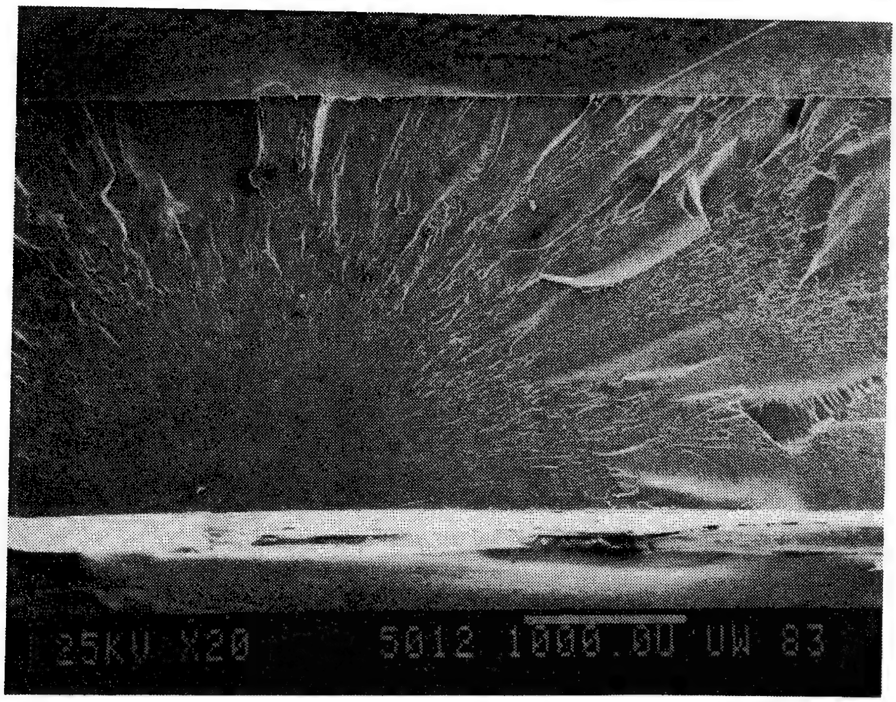


Figure D6. Fibredux 914 Neat Epoxy Tension, Specimen No. LTDB2X, 54°C, Dry.

No discernible initiation site can be seen in the smooth area of this failed specimen.

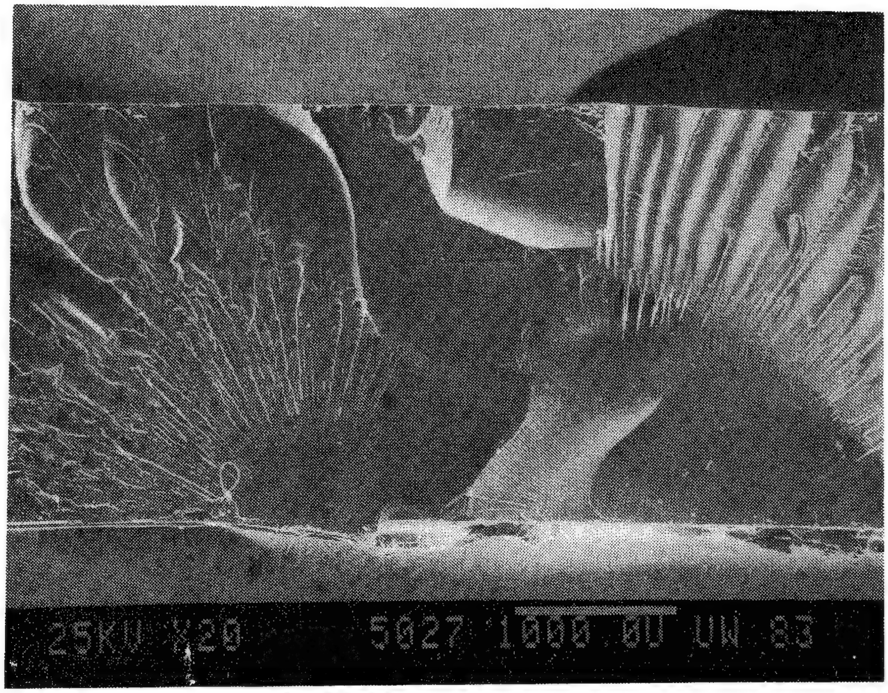


Figure D7. 2220-1 Neat Epoxy Tension, Specimen No. LTDA02, 23°C, Dry.

The smooth region of suspected failure initiation is located in the lower, slightly left of center part of this photograph. No discernible site is evident within the smooth region. The large region in the right half of the photograph is the surface where the characteristic chip was expelled at failure.

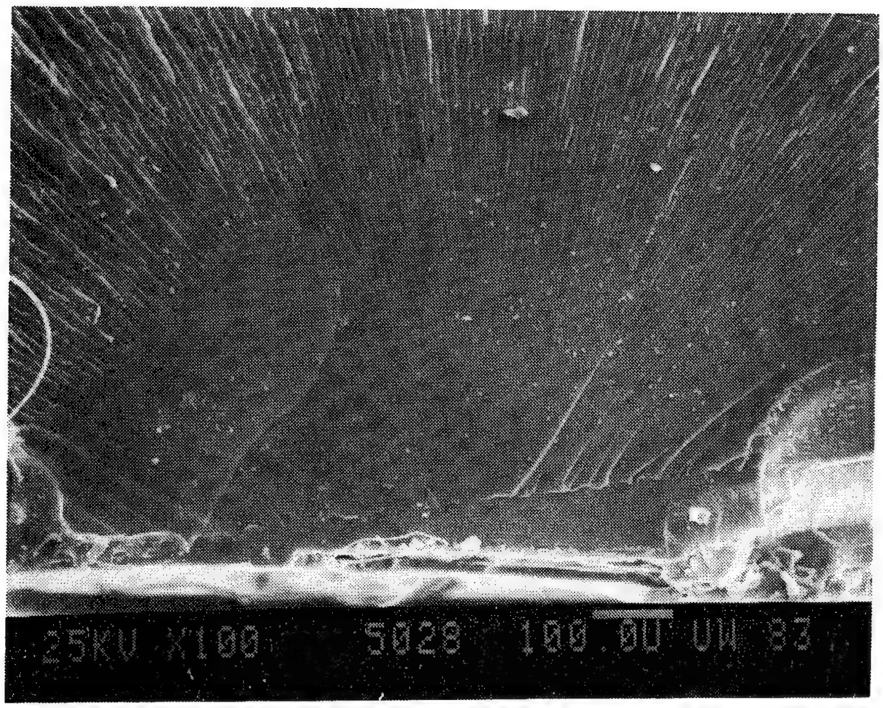


Figure D8. 2220-1 Neat Epoxy Tension, Specimen No. LTDA02, 23°C, Dry.

The very small smooth region at the lower edge of the specimen, surrounded by the transition region, is shown in this close-up of Figure D7.

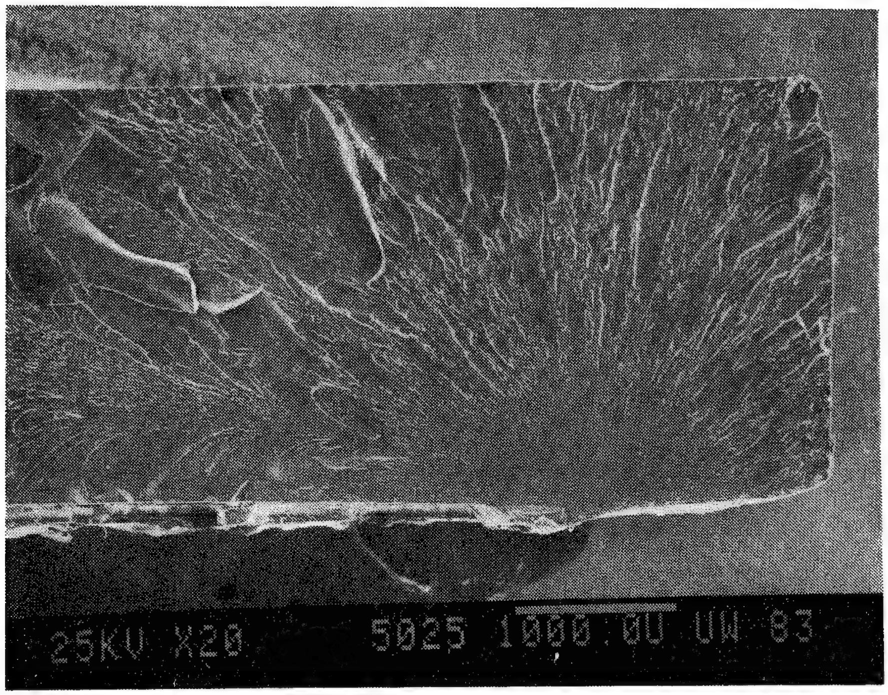


Figure D9. 2220-1 Neat Epoxy Tension, Specimen No. LTDB02, 54°C, Dry.

No specific failure site is apparent for this failed specimen.

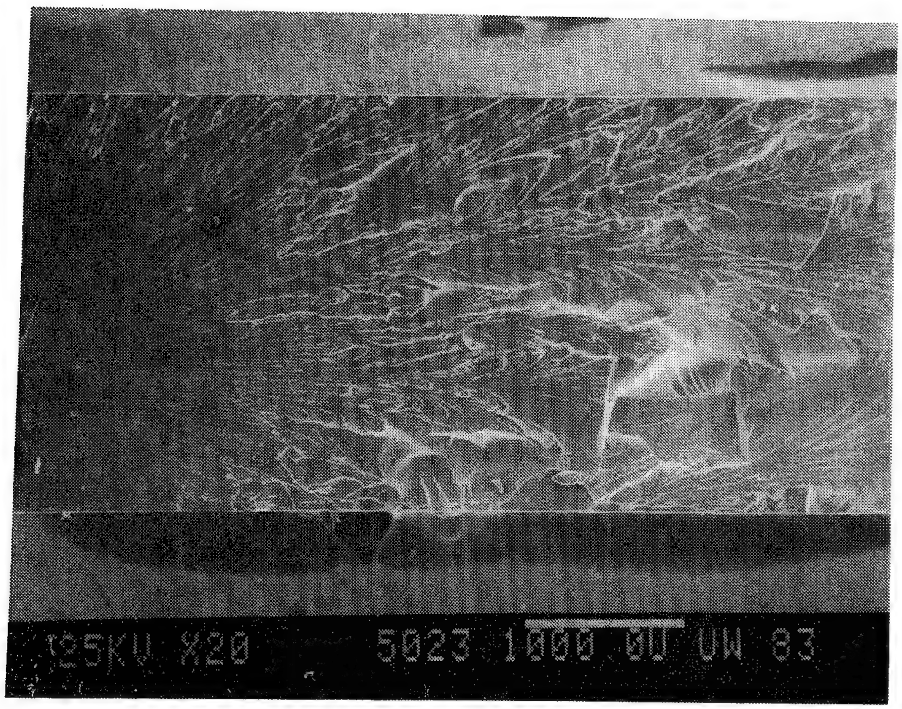


Figure D10. 2220-1 Neat Epoxy Tension, Specimen No. LTWC03, 82°C, Moisture-Saturated.

Very little, if any, difference was seen between the wet and dry failures at 82°C for the 2220-1 epoxy system.

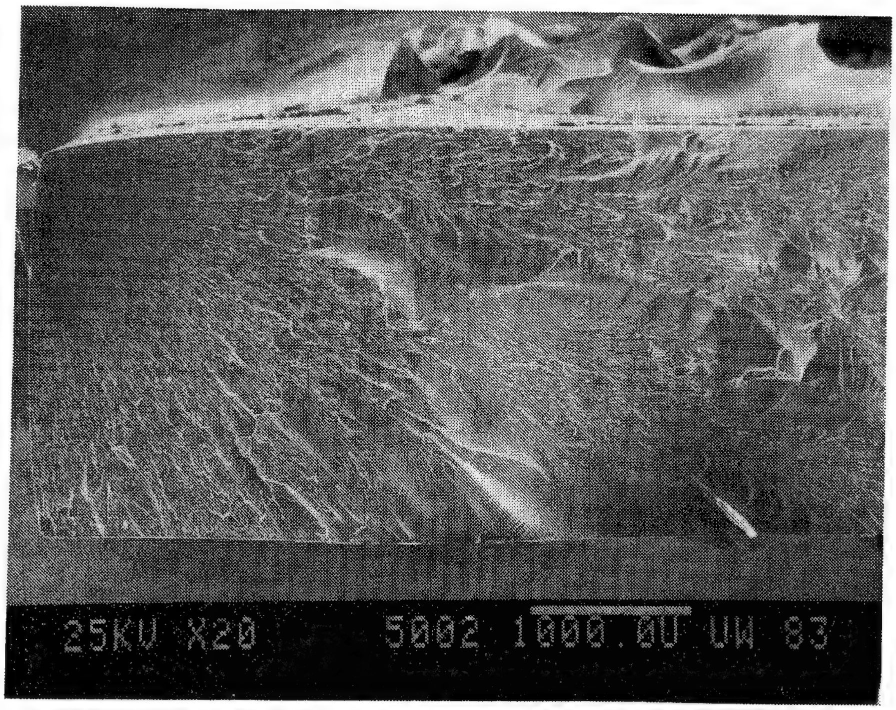


Figure D11. 2220-3 Neat Epoxy Tension, Specimen No. LTDA12, 23°C, Dry.

The fracture initiation site is located in the upper left corner of the specimen. It is surrounded by the transition and rough areas with the chip area on the right-hand side and partially out of the field of view of the photograph.

Figure D12. 2220-3 Neat Epoxy Tension, Specimen No. LTDA13, 23°C, Dry.

This specimen has a large chip missing in the lower right-hand corner, with the failure initiation site located to its left.

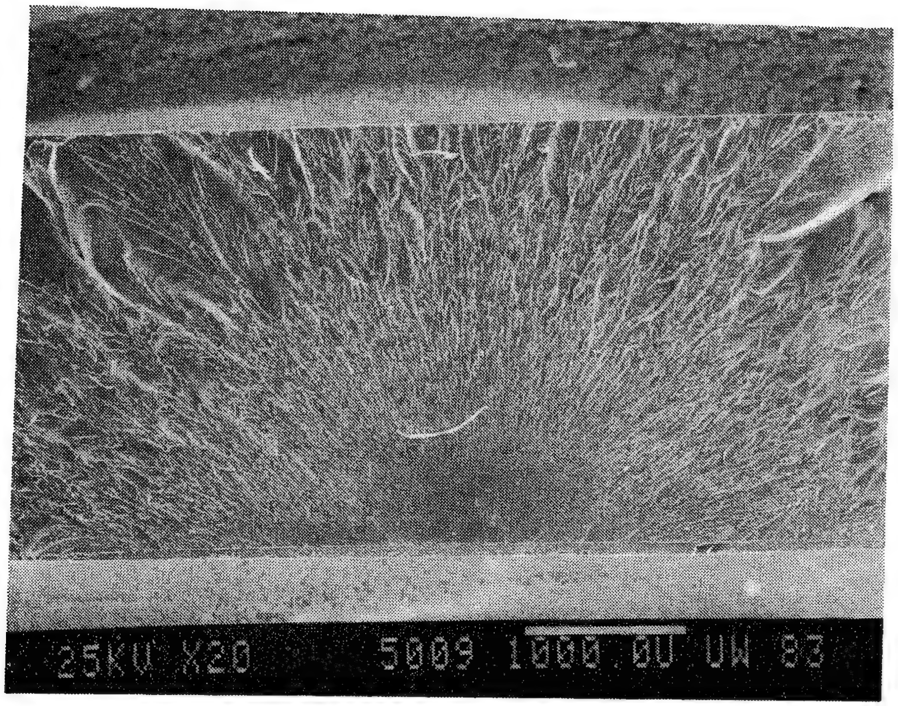


Figure D13. 2220-3 Neat Epoxy Tension, Specimen No. LTDA15, 23°C, Dry.

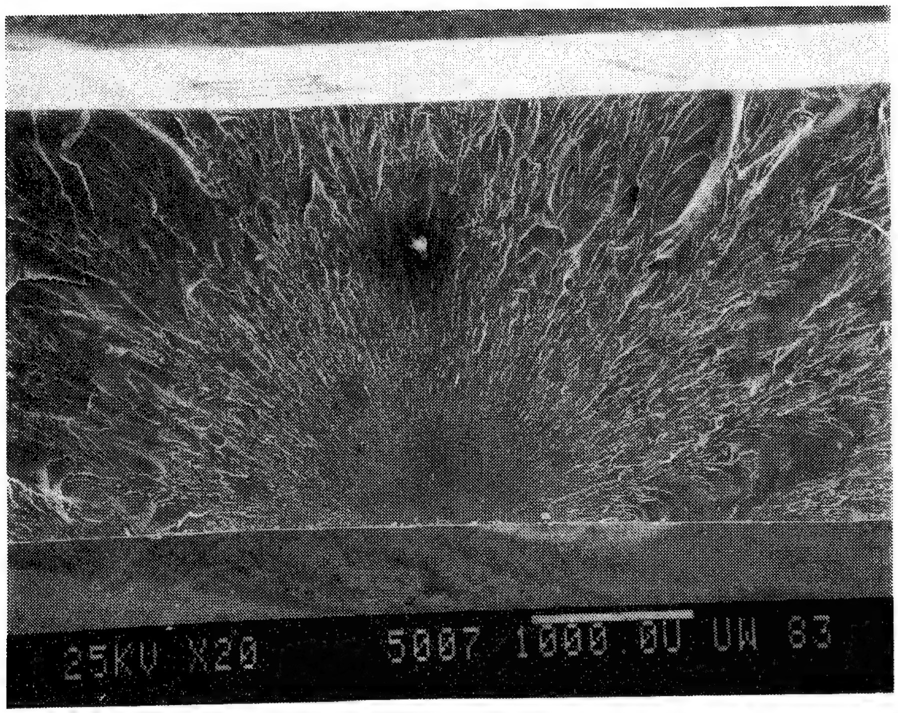


Figure D14. 2220-3 Neat Epoxy Tension, Specimen No. LTDA16, 23°C, Dry.

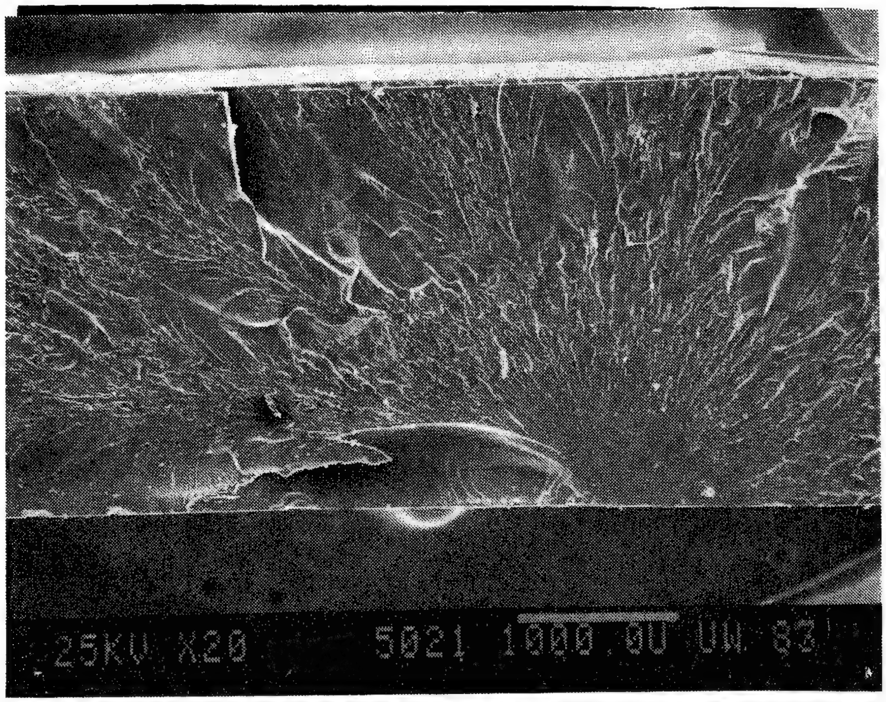


Figure D15. 2220-3 Neat Epoxy Tension, Specimen No. LTDA17, 23°C, Dry.

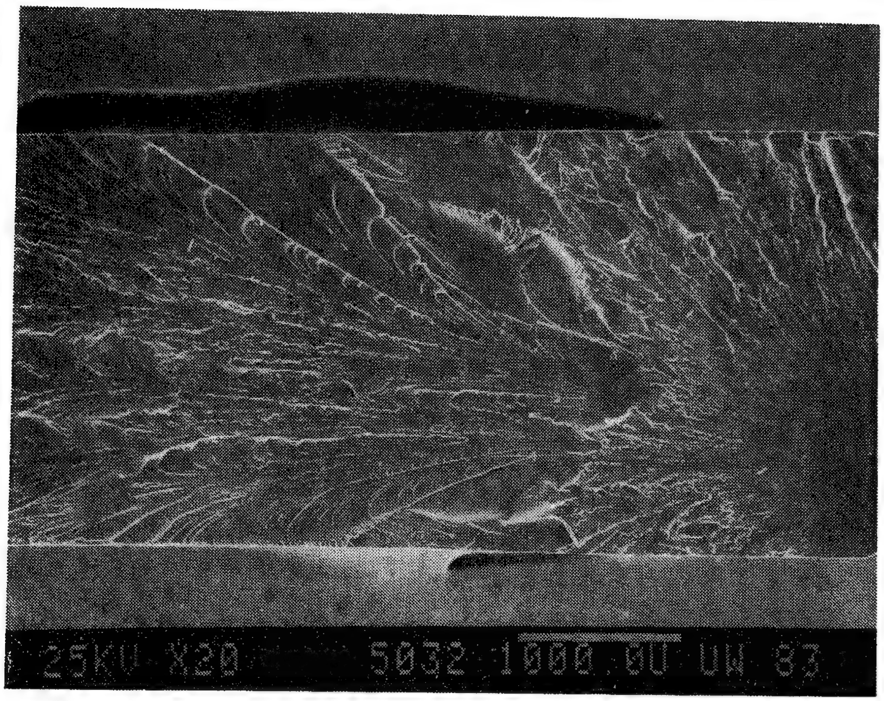


Figure D16. 2220-3 Neat Epoxy Tension Specimen No. LTWB13, 54°C, Moisture-Saturated.

This specimen appears very similar to the dry failed specimen at 54°C.

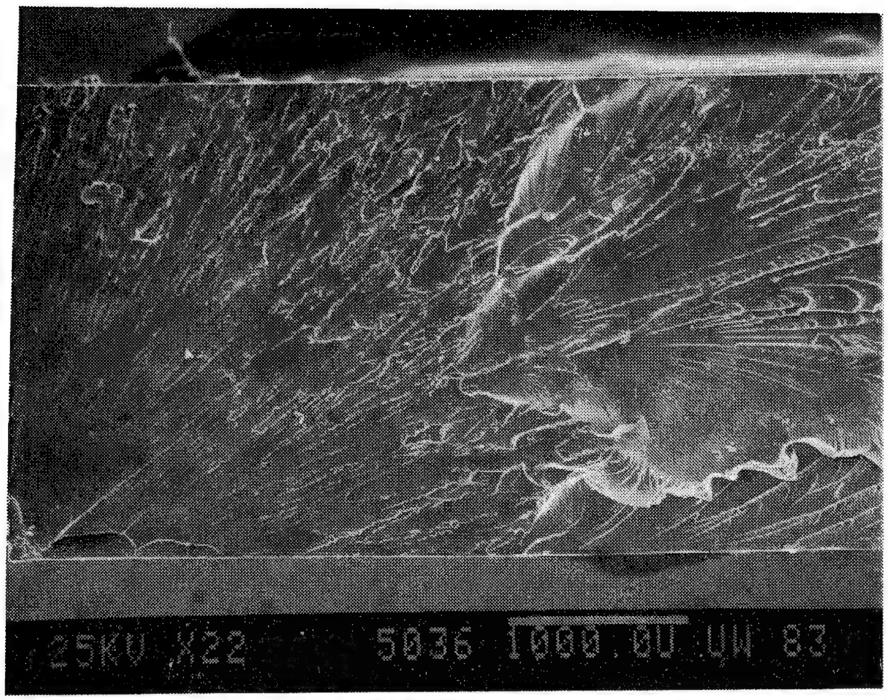


Figure D17. 2220-3 Neat Epoxy Tension, Specimen No. LTWC11, 82°C, Moisture-Saturated.

This specimen failure appears quite similar to the dry 82°C specimen failures except for the small internal void within the smooth region on the left.

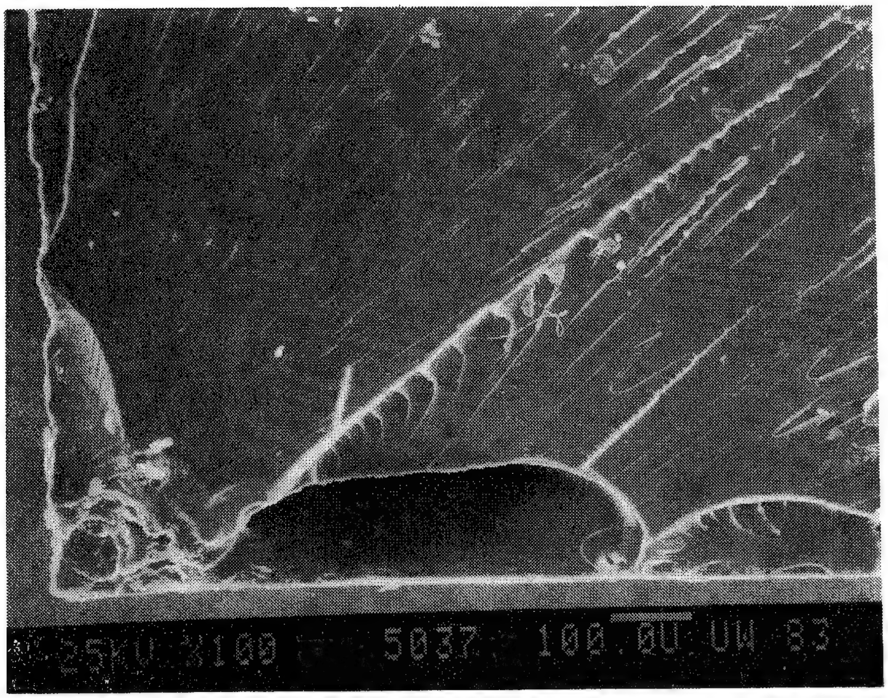


Figure D18. 2220-3 Neat Epoxy Tension, Specimen No. LTWC11, 82°C, Moisture-Saturated.

This closeup of Figure D17 shows the void area directly in the corner next to a missing chip area.

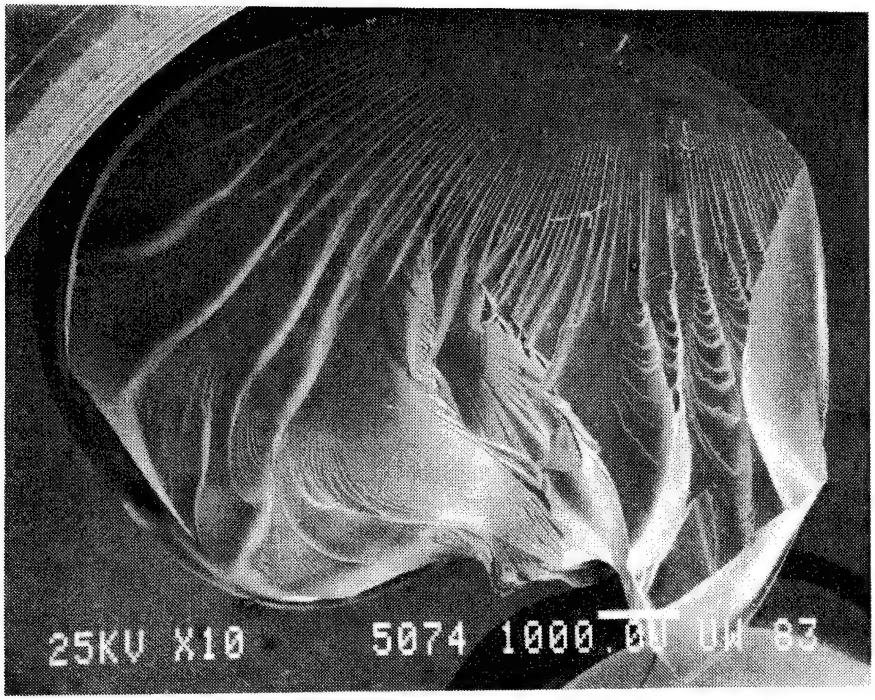


Figure D19. 3502 Neat Epoxy Torsional Shear, 54°C, Moisture-Saturated.

This failure is quite similar to those observed in the 54°C, dry specimens.

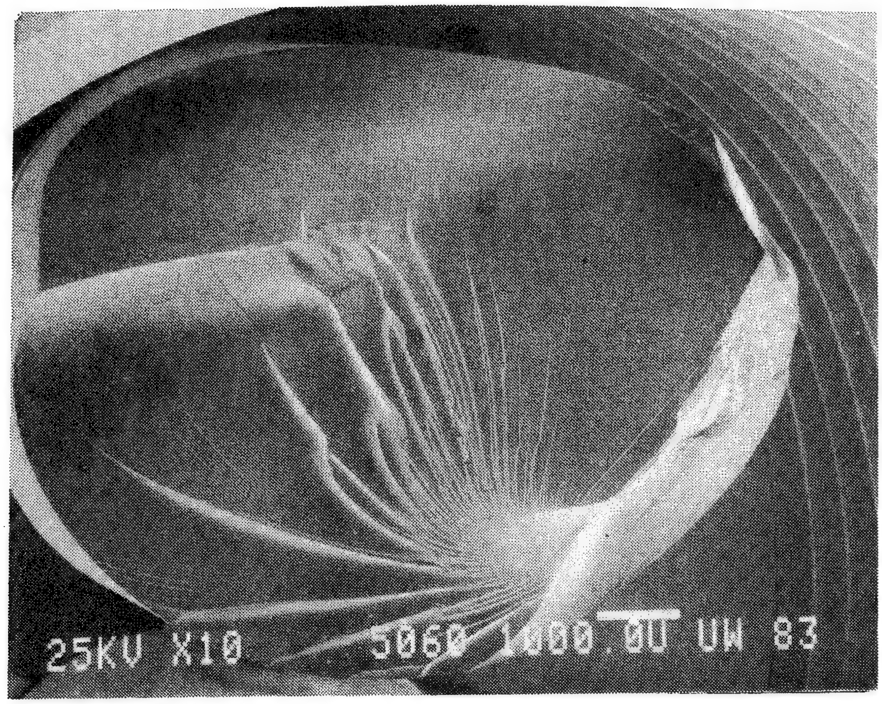


Figure D20. 3502 Neat Epoxy Torsion Shear, 82°C, Dry.

This failure has a much smoother appearance away from the failure initiation site and transition zone in the lower right-hand corner of the photograph.

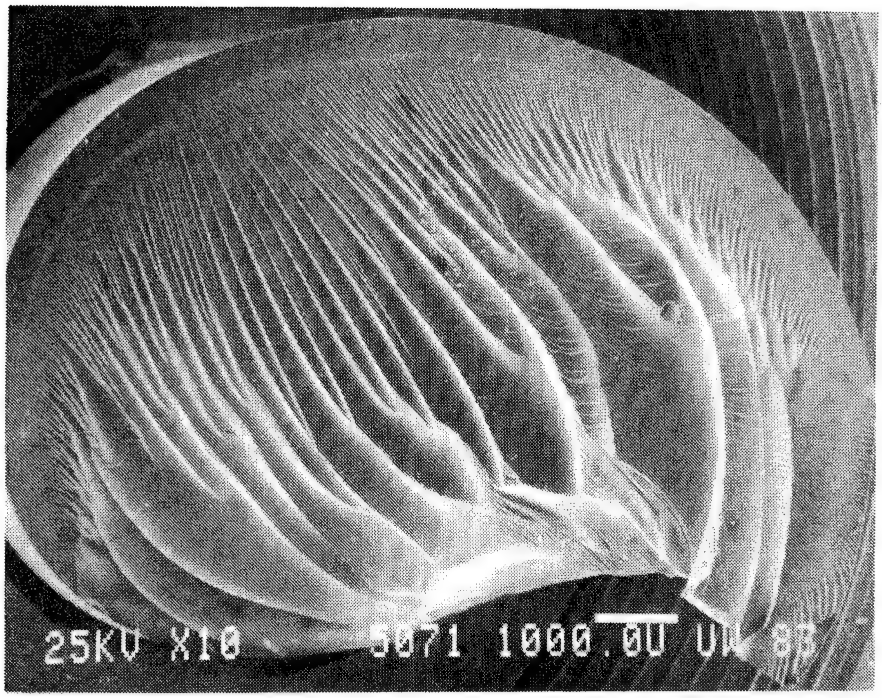


Figure D21. 3502 Neat Epoxy Torsional Shear, 82°C, Moisture-Saturated.

A smooth area extending around the perimeter of the specimen, which is the most highly stressed region in a torsion test, is shown. The transition region extends inward from this surface region.

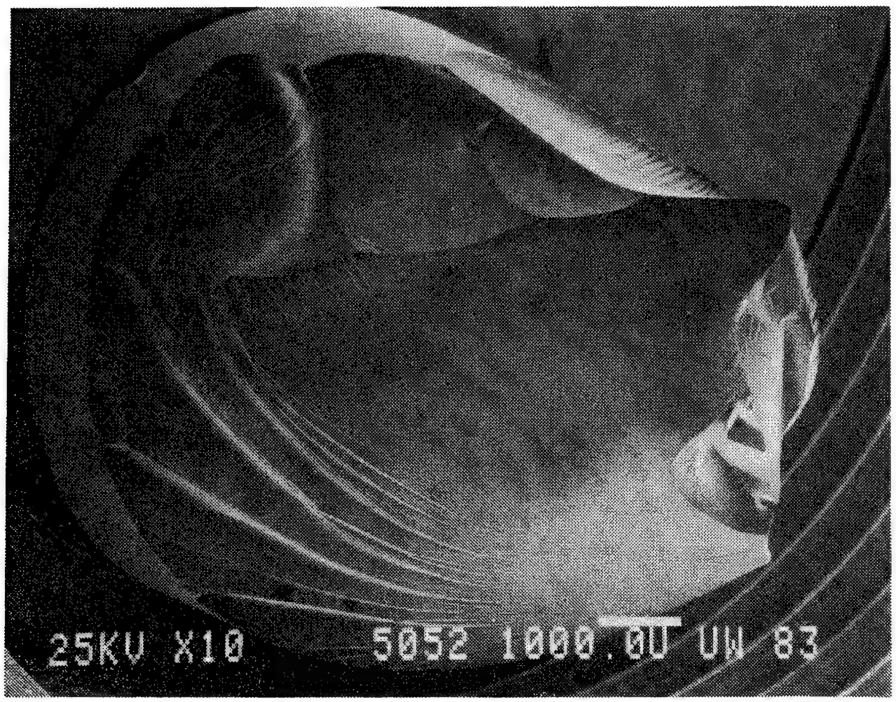


Figure D22. Fibredux 914 Neat Epoxy Torsional Shear, 23°C, Dry.

This failure surface indicates many missing pieces.

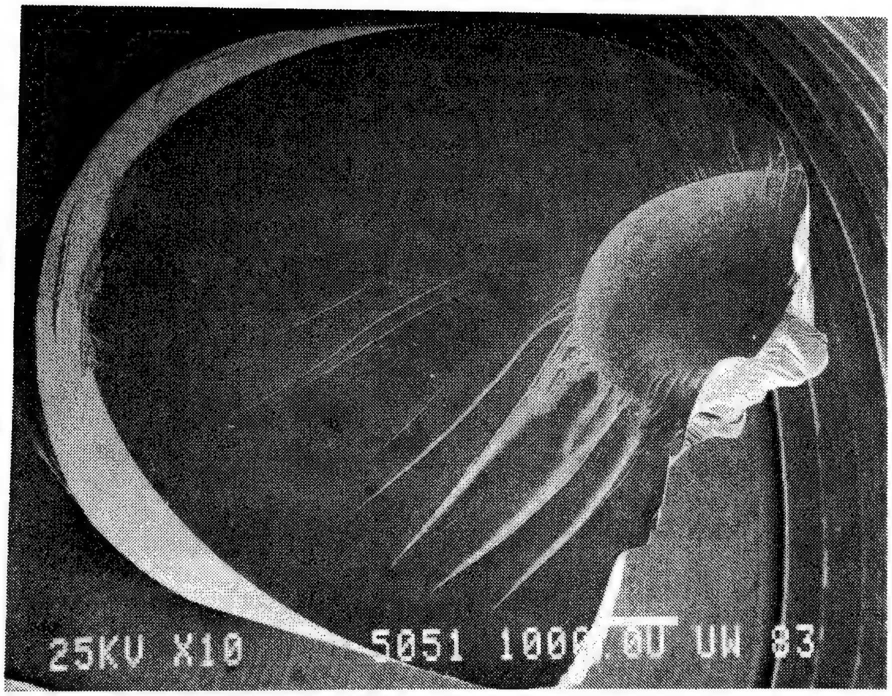


Figure D23. Fibredux 914 Neat Epoxy Torsional Shear, 54°C, Dry.

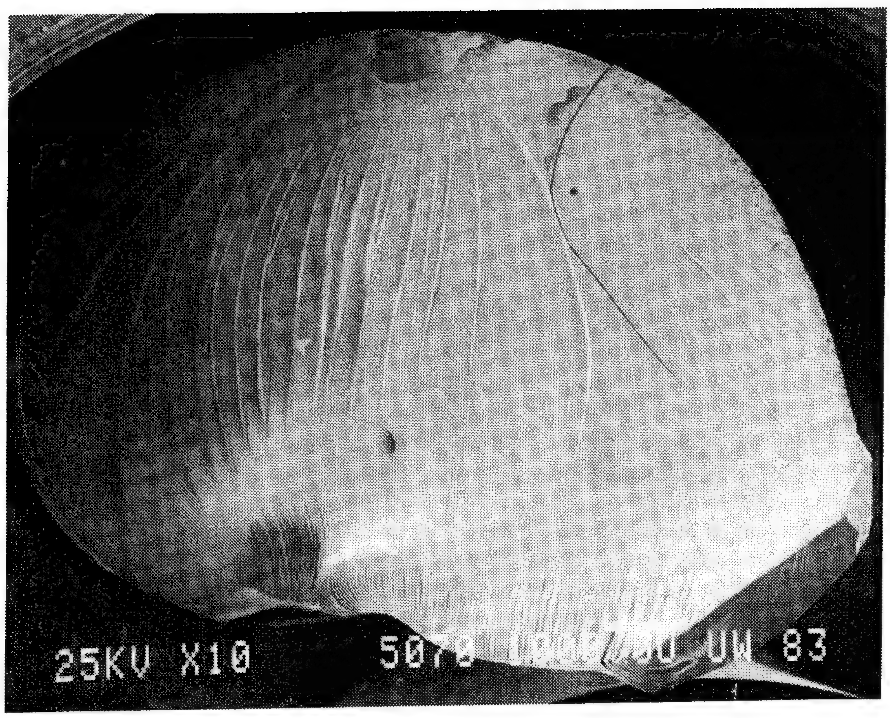


Figure D24. Fibredux 914 Neat Epoxy Torsional Shear 54°C, Moisture-Saturated.

Post failure cracking due to dry-out is seen in the upper right-hand corner of this cross section.

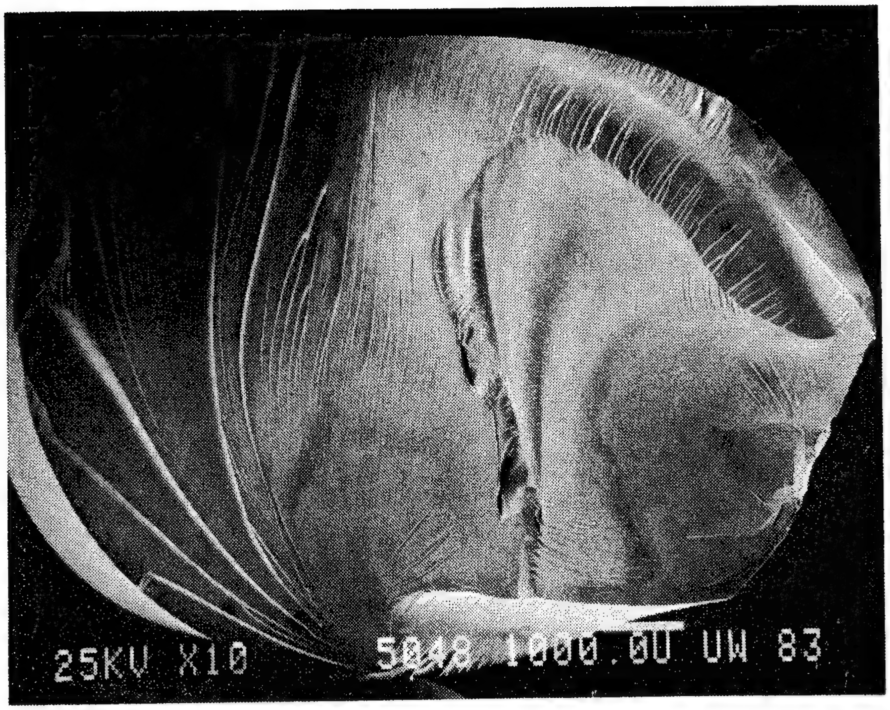


Figure D25. Fibredux 914 Neat Epoxy Torsional Shear, 82°C, Dry.

More evidence of the characteristic transition region and the striations associated with it is seen.

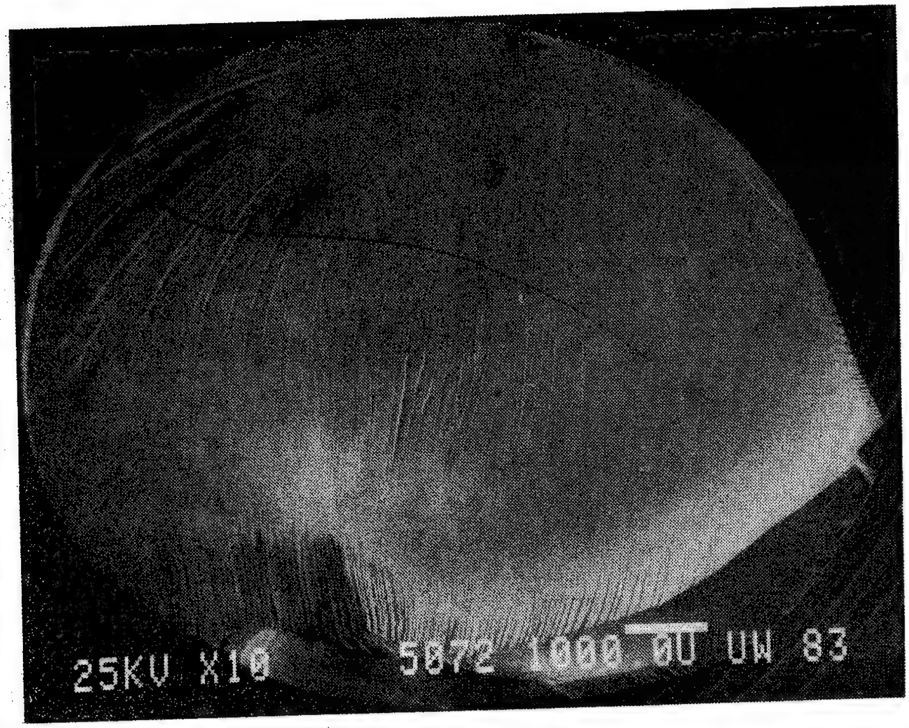


Figure D26. Fibredux 914 Neat Epoxy Torsional Shear, 82°C, Moisture-Saturated.

A very large post-failure crack is evident through this specimen due to high stress gradients induced during drying out after failure. Note also the loose pieces of resin extending over the crack in the upper left.

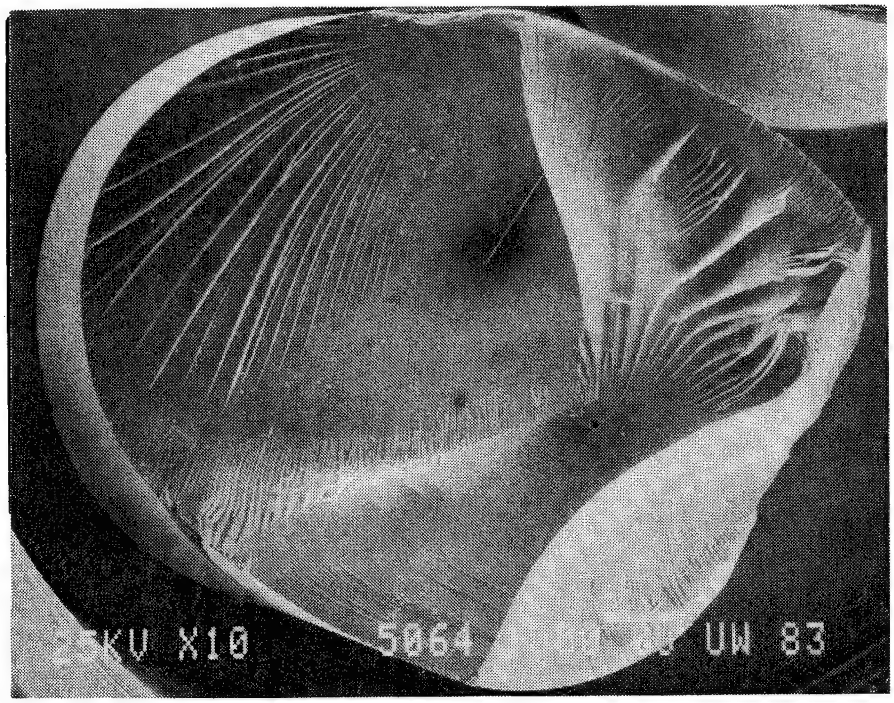


Figure D27. 2220-1 Neat Epoxy Torsional Shear, 23°C, Moisture-Saturated.

Failure probably initiated at the upper center surface of this specimen.

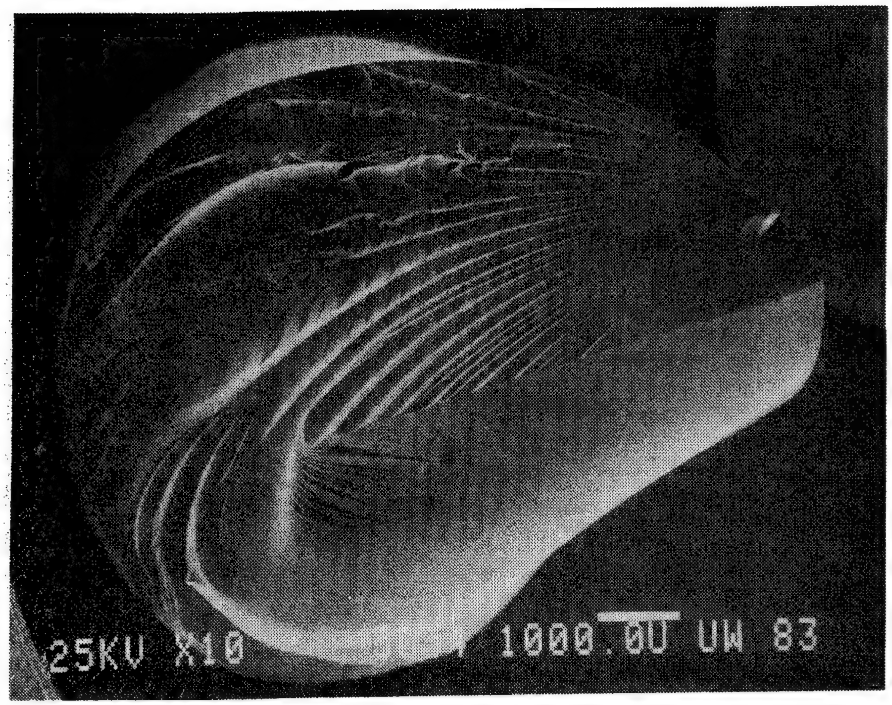


Figure D28. 2220-1 Neat Epoxy Torsional Shear, 54°C, Dry.

Failure probably began at the upper right-hand surface of this specimen.

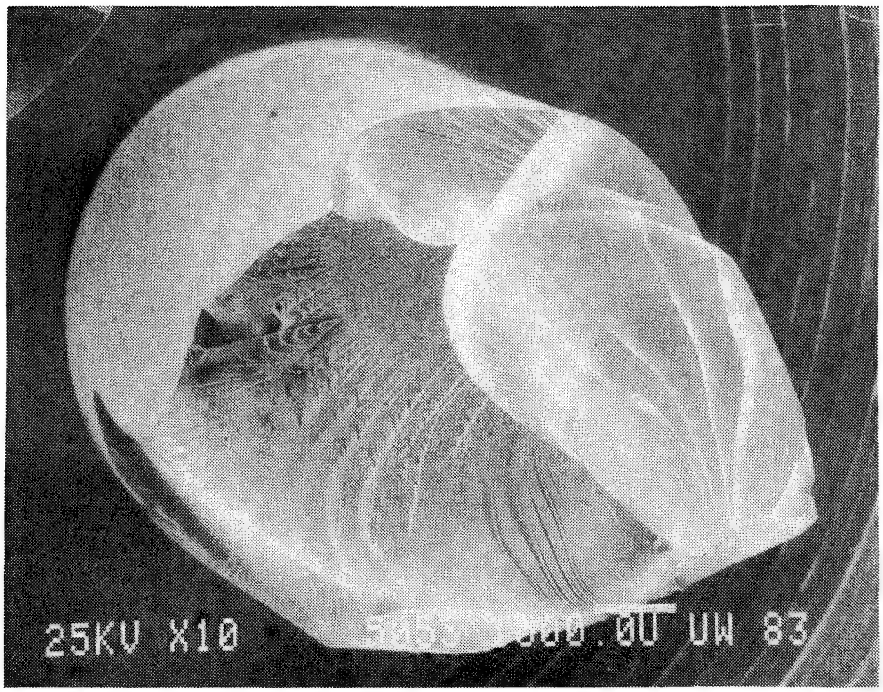


Figure D29. 2220-1 Neat Epoxy Torsional Shear, 82°C, Dry.

The location of the initial failure site was lost with the chip that broke loose from the upper right side of this specimen during fracture.

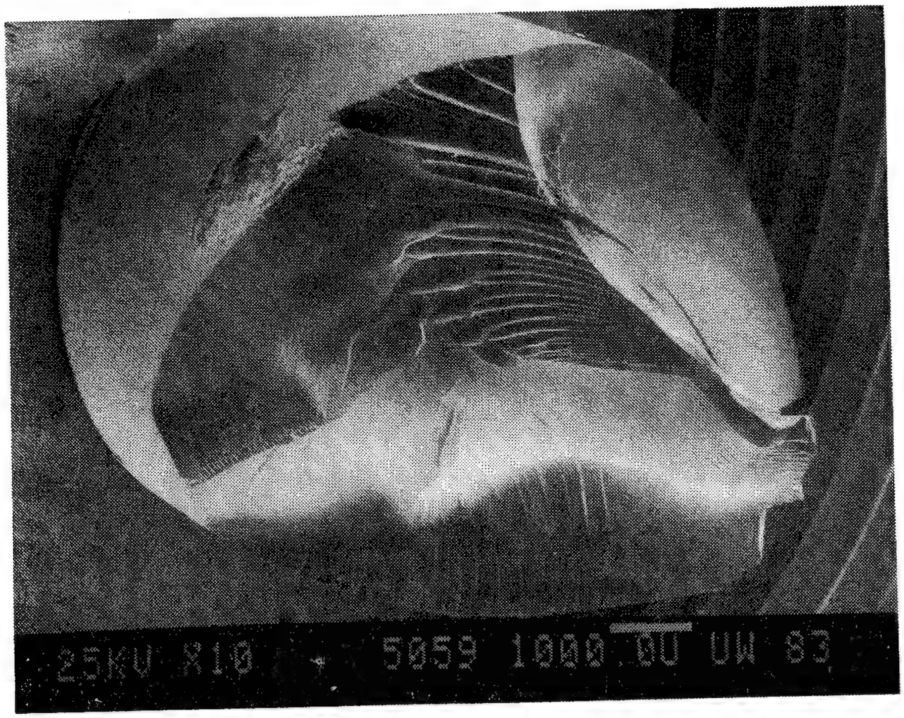


Figure D30. 2220-3 Neat Epoxy Torsional Shear, 23°C, Dry.

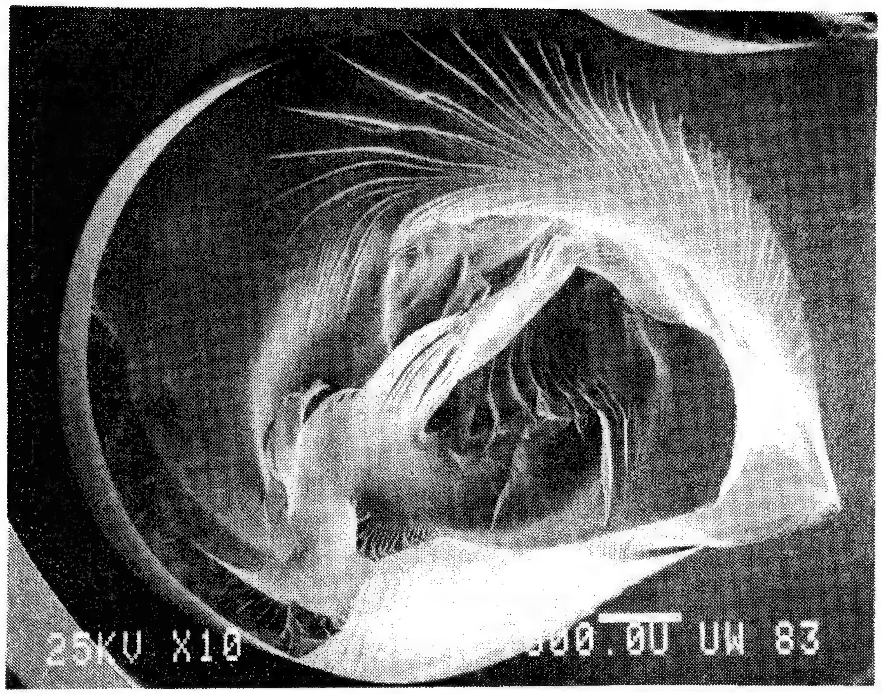


Figure D31. 2220-3 Neat Epoxy Torsional Shear, 23°C, Moisture-Saturated.

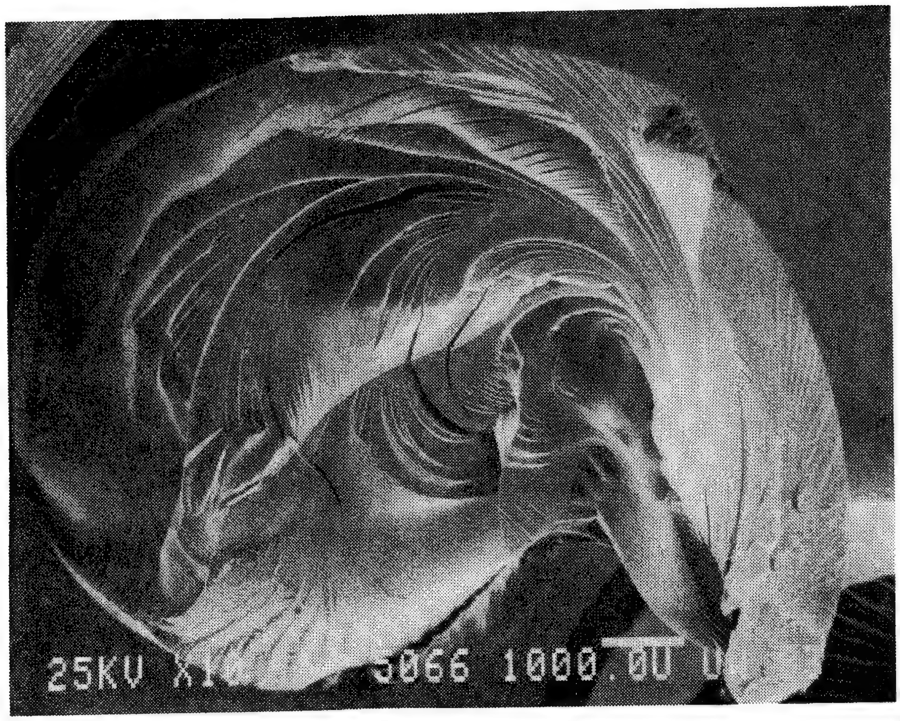


Figure D32. 2220-3 Neat Epoxy Torsional Shear, 82°C, Moisture-Saturated.

The many cracks present in this specimen will be noted. It is not known if they occurred at failure, or after due to moisture-induced dry-out stresses. The latter is probable.

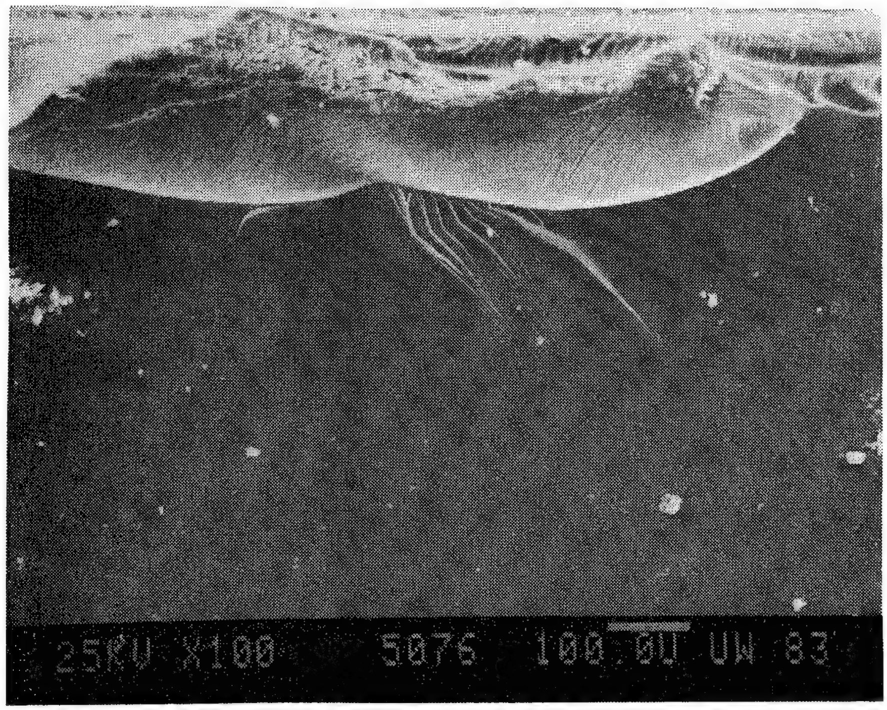


Figure D33. 2220-3 Neat Epoxy Fracture Toughness, 23°C, Dry.

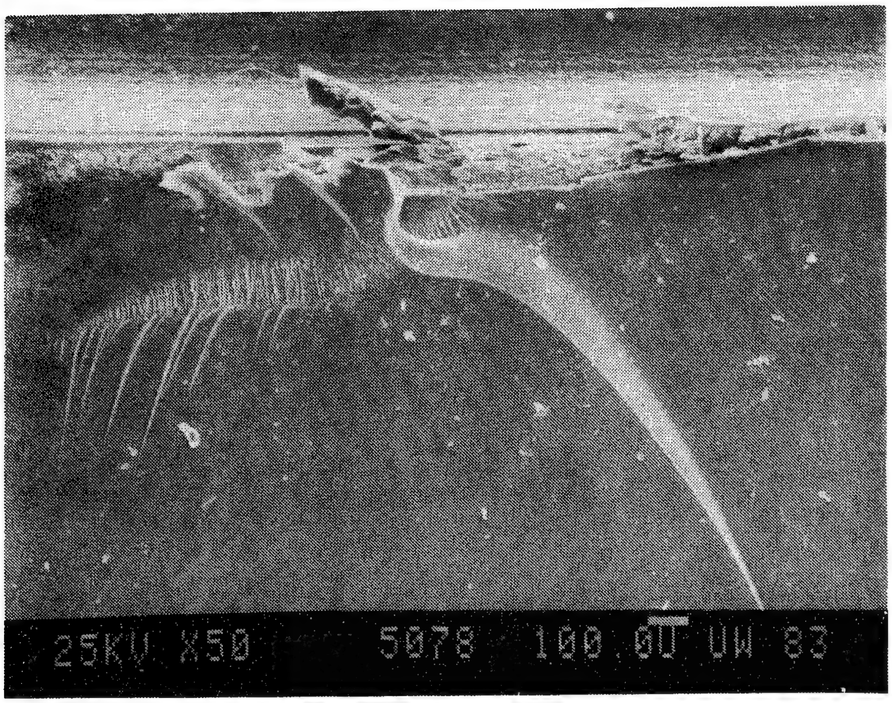


Figure D34. 2220-3 Neat Epoxy Fracture Toughness, 82°C, Dry.

The notch area is located at the top of this photograph.

APPENDIX E

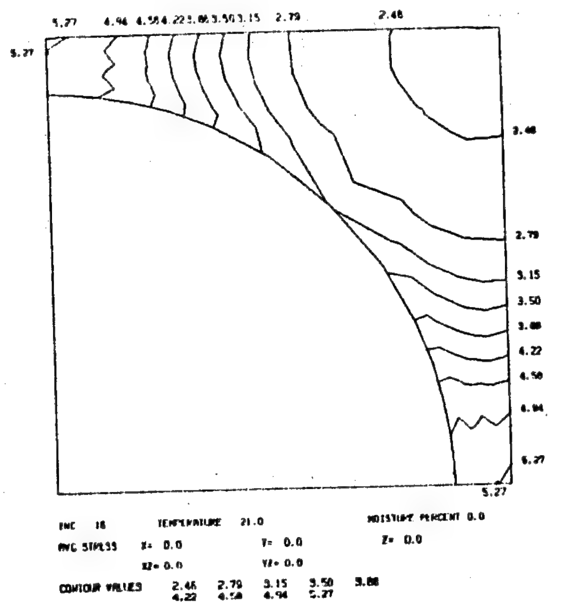
PLOTS OF INTERNAL STRESS STATES IN AS4 GRAPHITE FIBER-REINFORCED

UNDIRECTIONAL COMPOSITES INCORPORATING

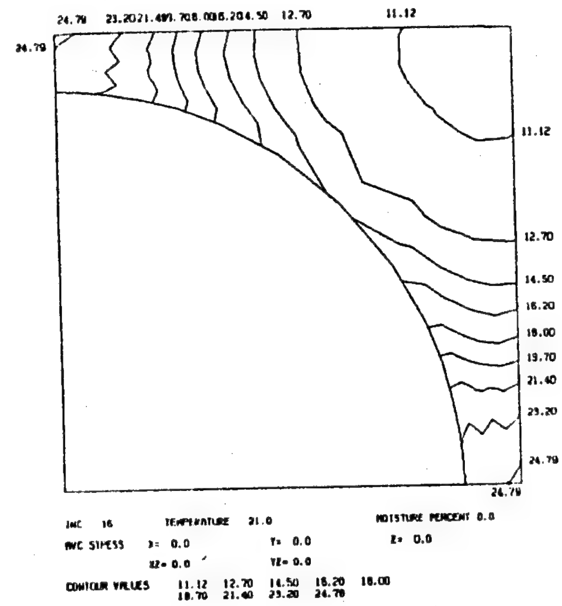
3502, 2220-3, and 914 MATRIX MATERIALS

APPENDIX E1

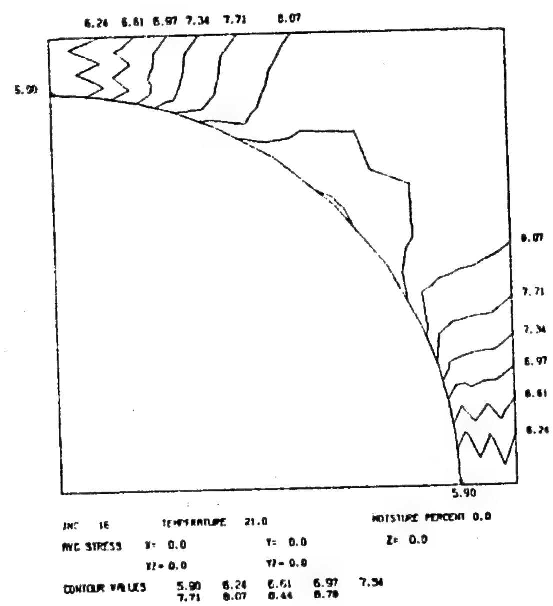
AS4/3502 GRAPHITE/EPOXY UNIDIRECTIONAL COMPOSITE



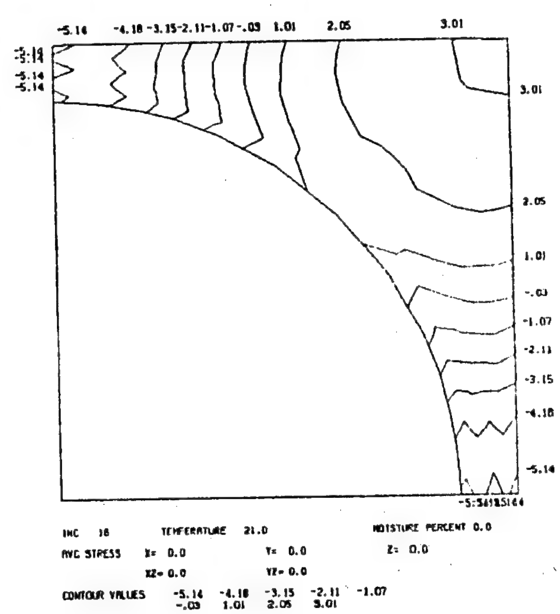
a) Octahedral Shear Stress (ksi)



b) Octahedral Shear Strain (10^{-3})

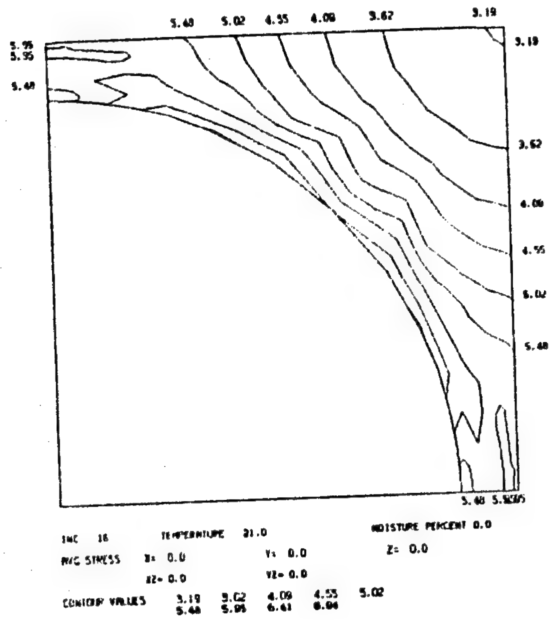


c) Maximum Principal Stress (ksi)

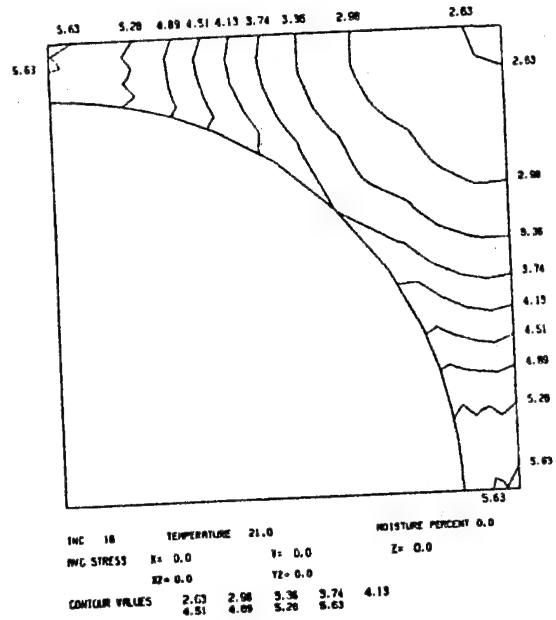


d) Minimum Principle Stress (ksi)

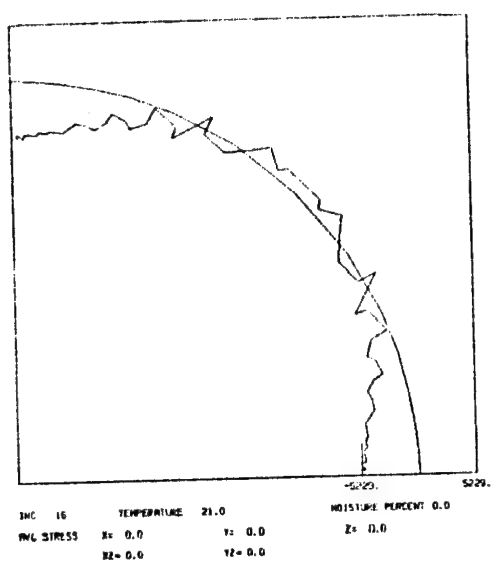
Figure E1. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



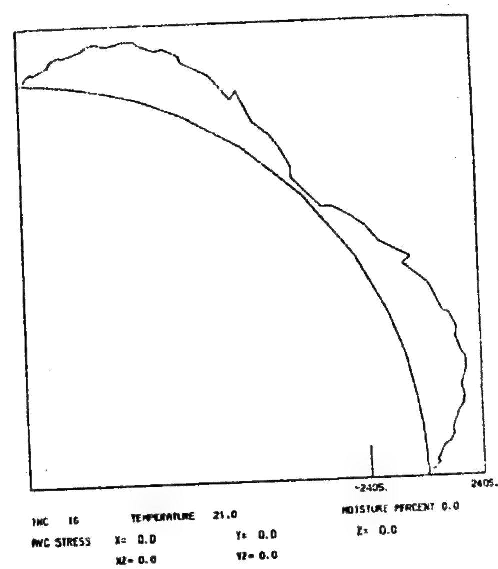
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

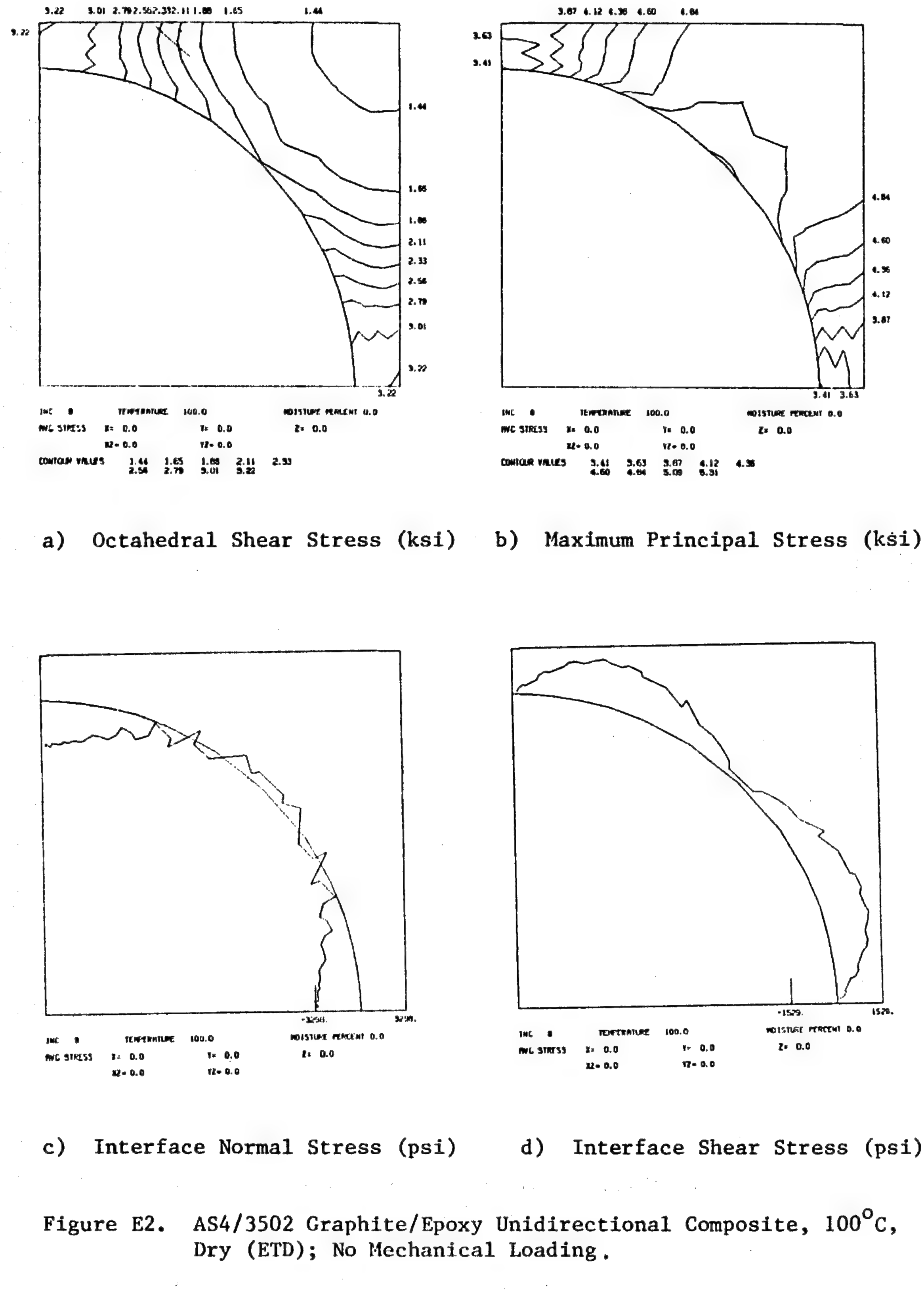


g) Interface Normal Stress (psi)



h) Interface Shear Stress (psi)

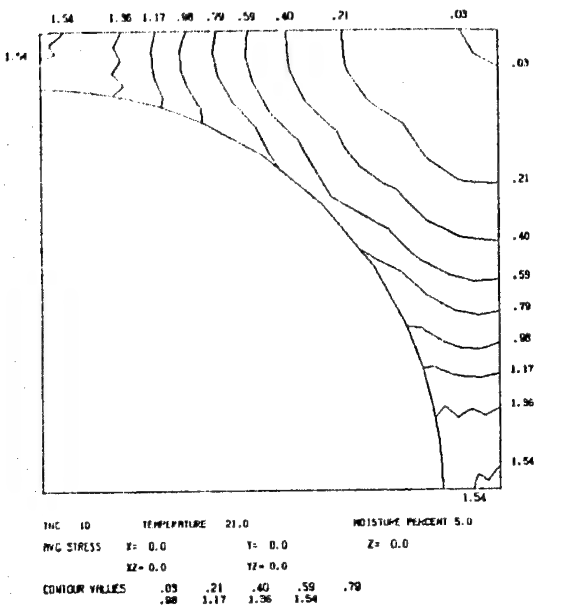
Figure E1 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



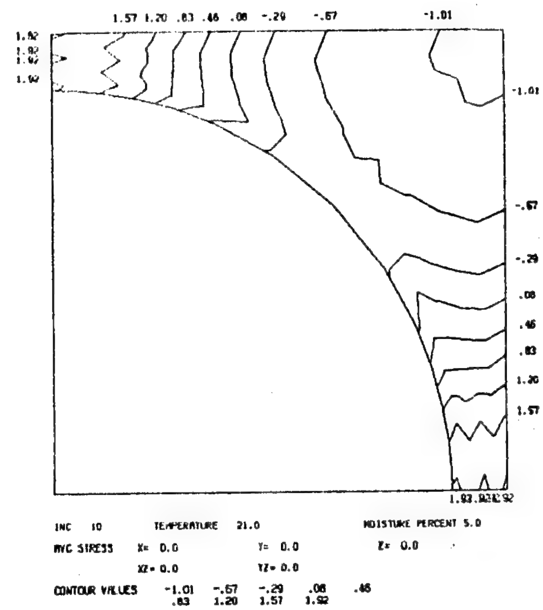
a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Interface Normal Stress (psi) d) Interface Shear Stress (psi)

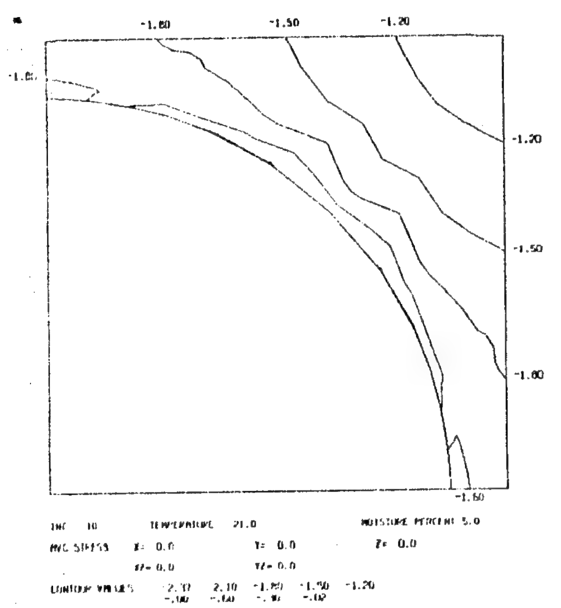
Figure E2. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); No Mechanical Loading.



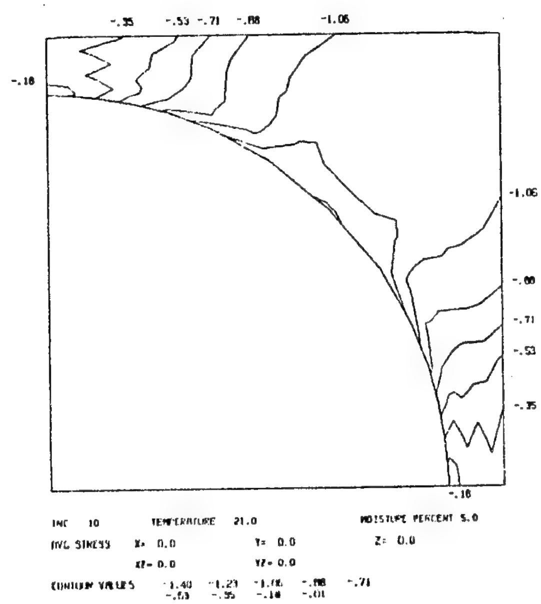
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

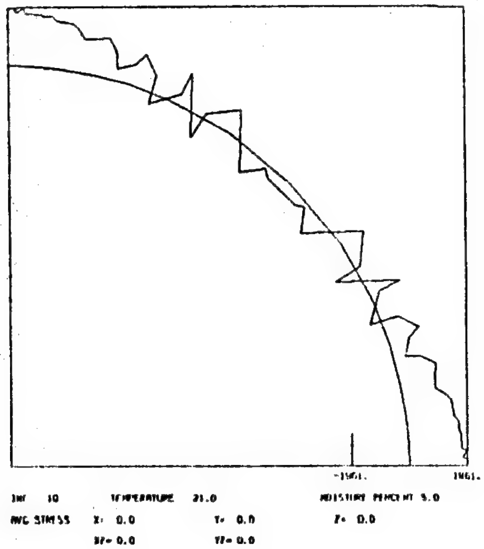


c) Minimum Principal Stress (ksi)

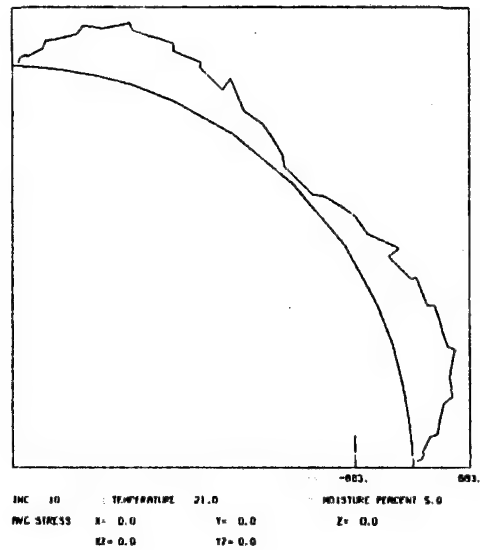


d) Intermediate Principal Stress (ksi)

Figure E3. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, 5.0 Percent Moisture (RTW); No Mechanical Loading.

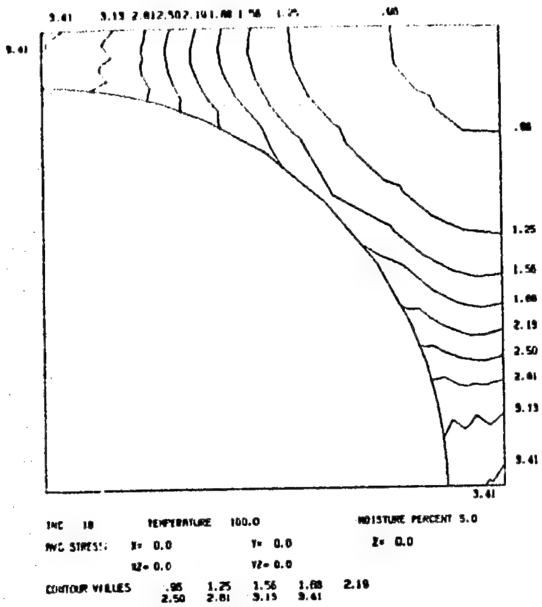


e) Interface Normal Stress (psi)

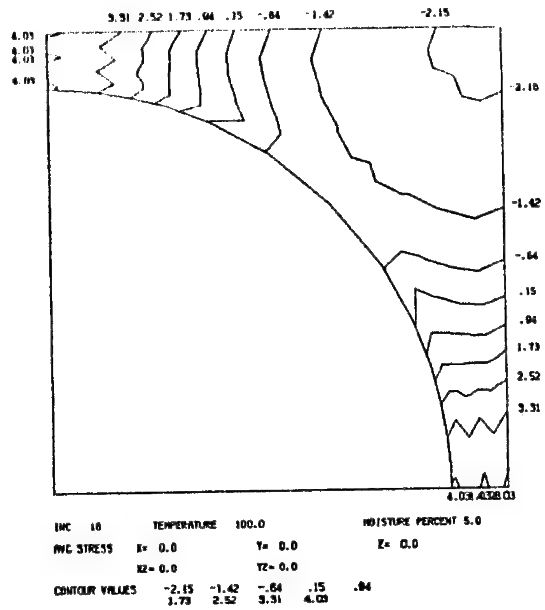


f) Interface Shear Stress (psi)

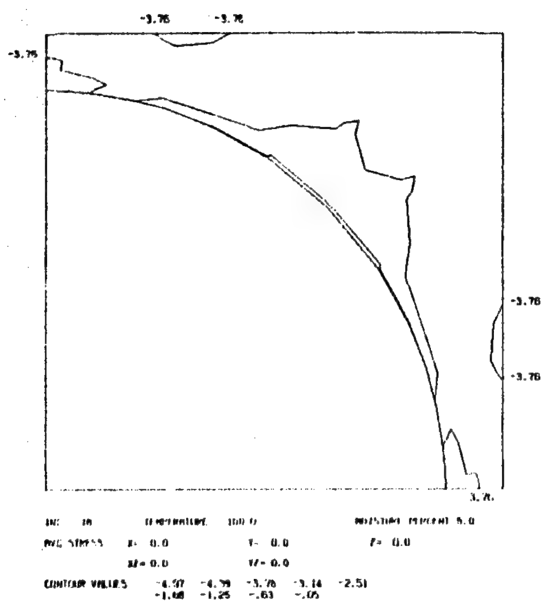
Figure E3 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, 5.0 Percent Moisture (RTW); No Mechanical Loading.



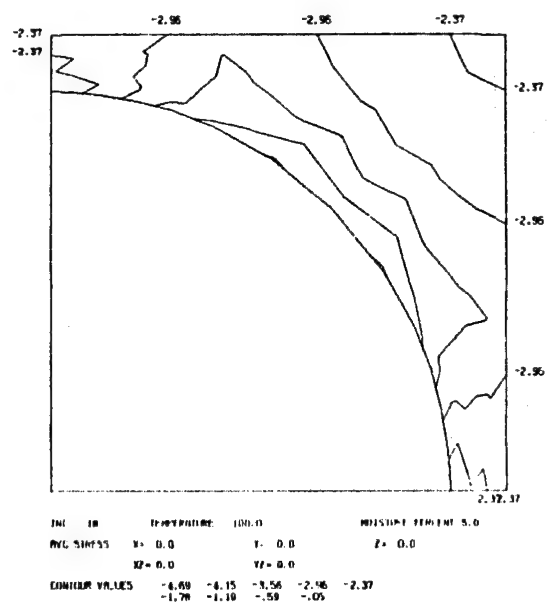
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

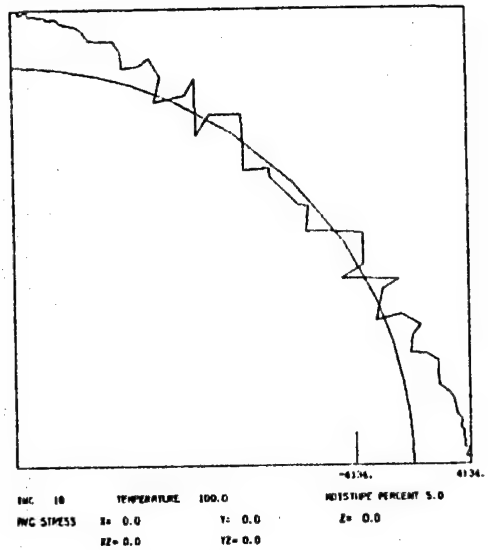


c) Minimum Principal Stress (ksi)

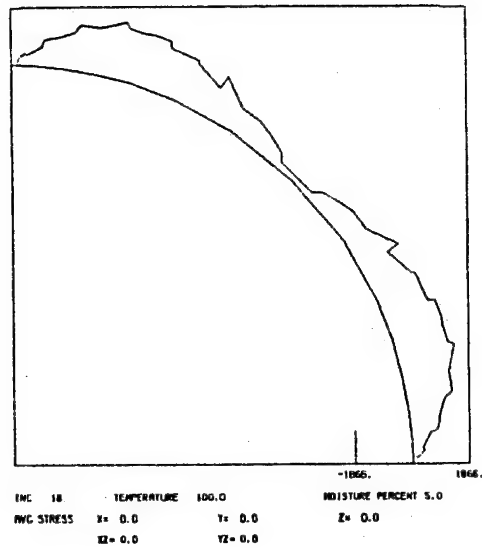


d) Intermediate Principal Stress (ksi)

Figure E4. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100^{o}C, 5.0 Percent Moisture (ETW); No Mechanical Loading.

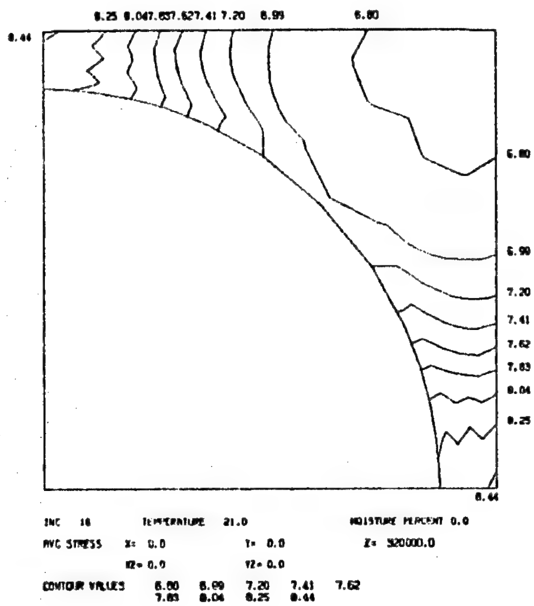


e) Interface Normal Stress (psi)

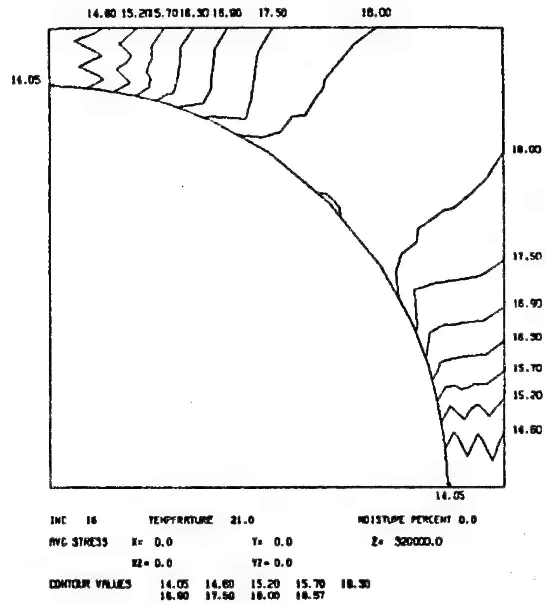


f) Interface Shear Stress (psi)

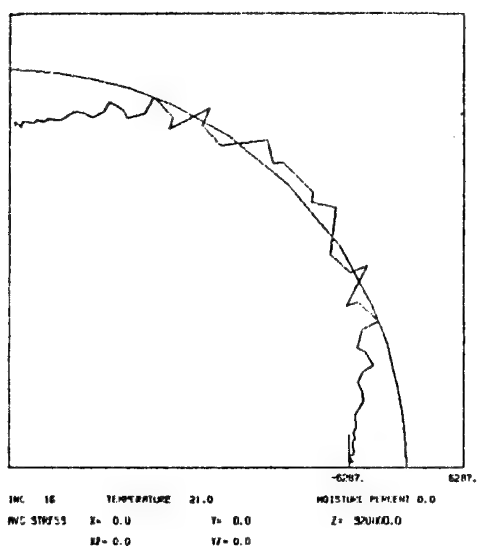
Figure E4 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); No Mechanical Loading.



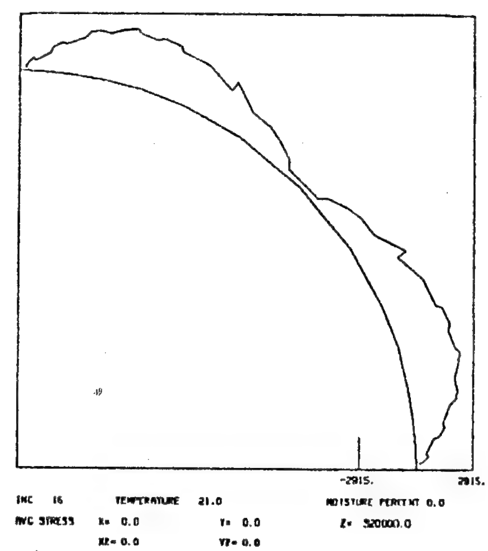
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

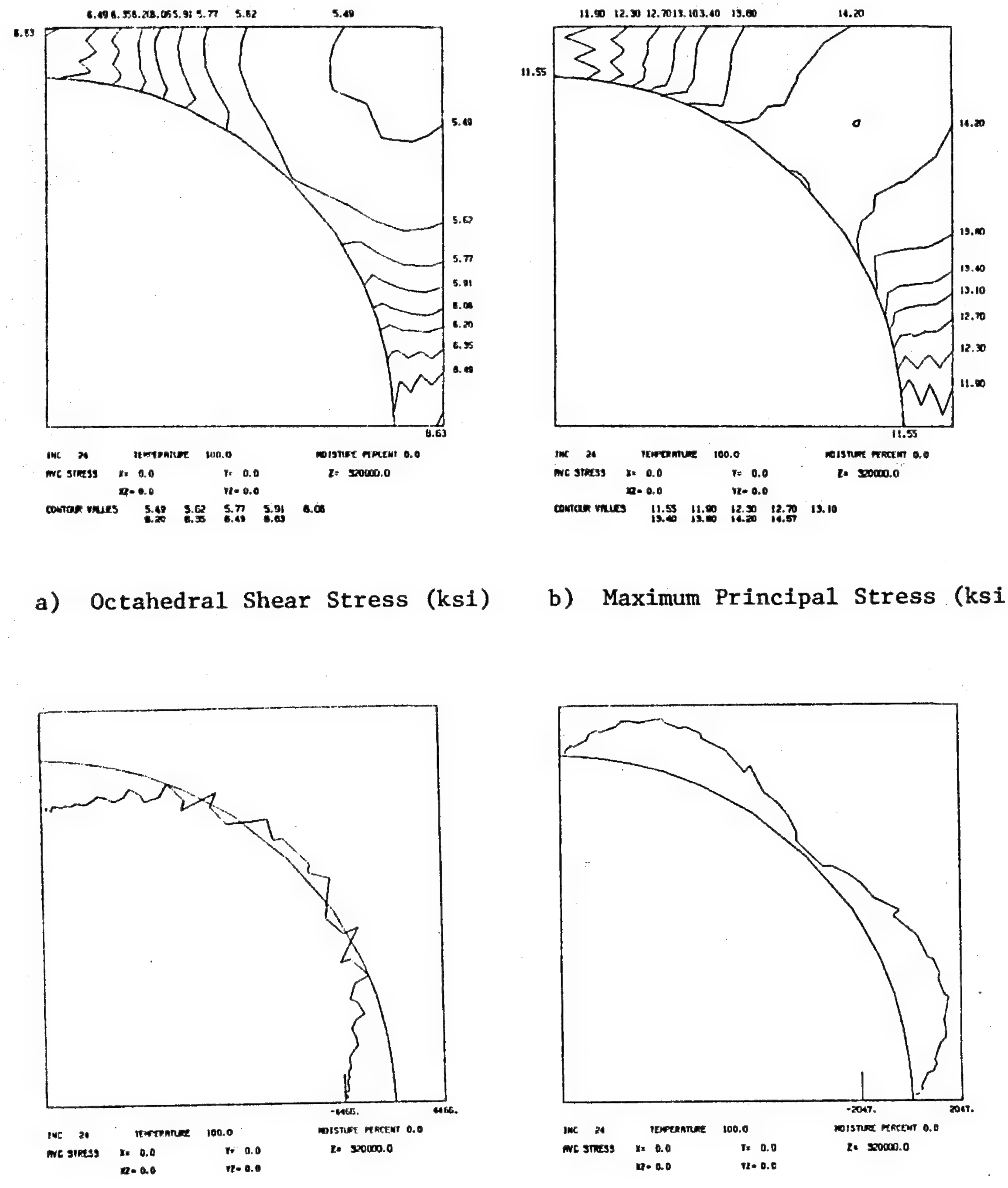


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

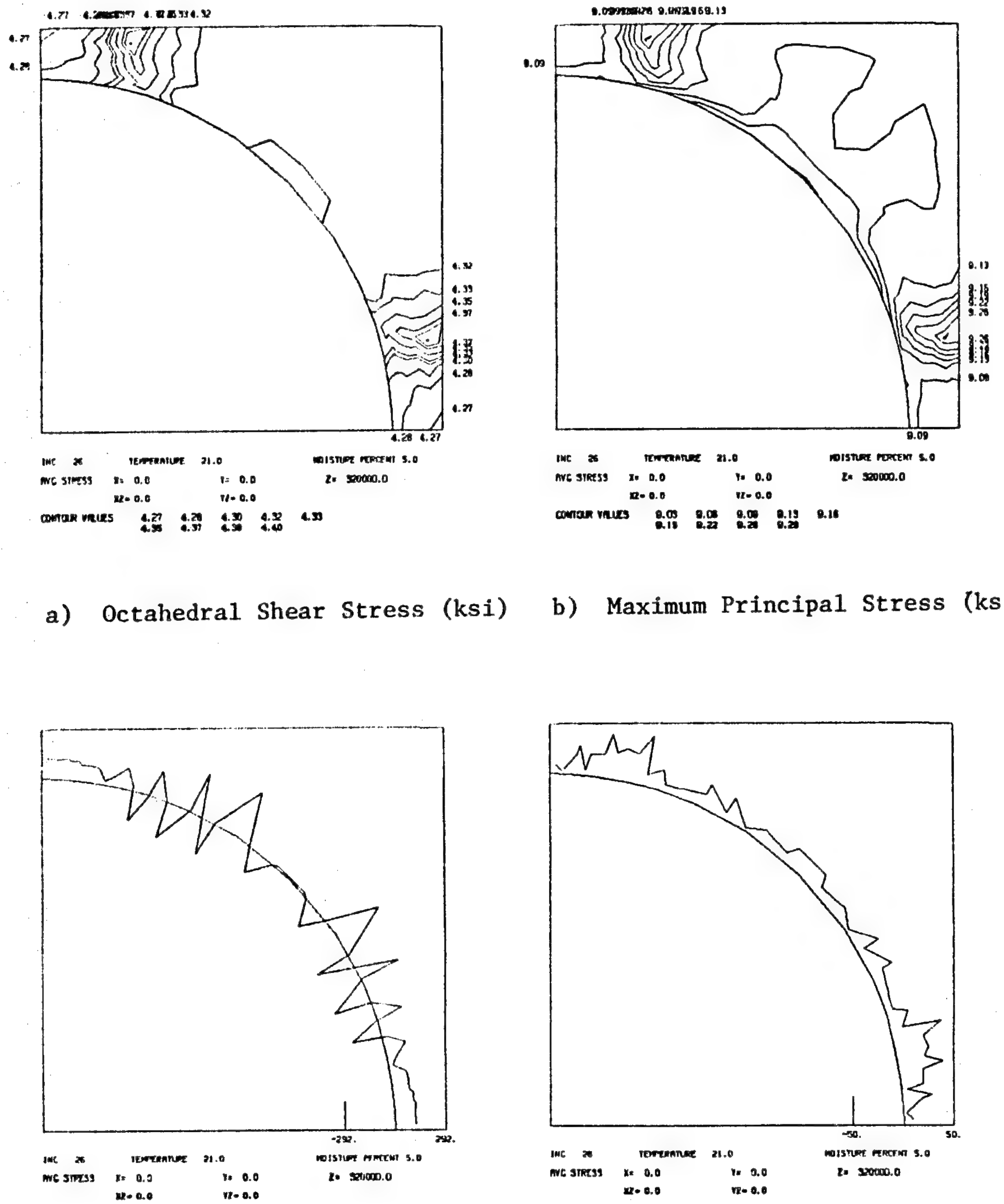
Figure E5. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Interface Normal Stress (psi) d) Interface Shear Stress (psi)

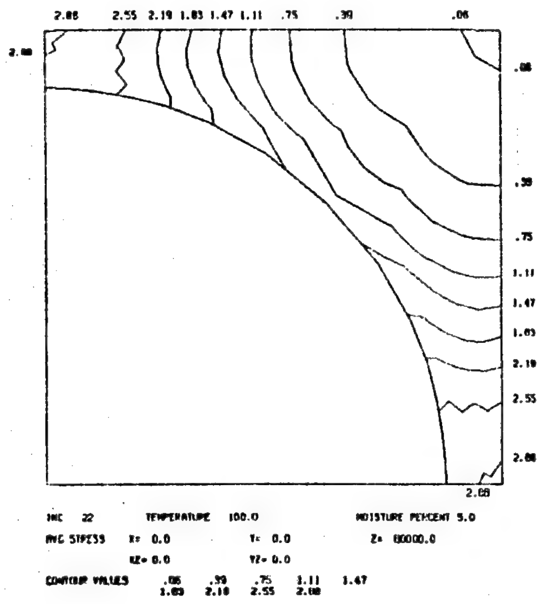
Figure E6. AS4/3502 Graphite/Epoxy Unidirectional Composite, $100^{\circ}C$, Dry (ETD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



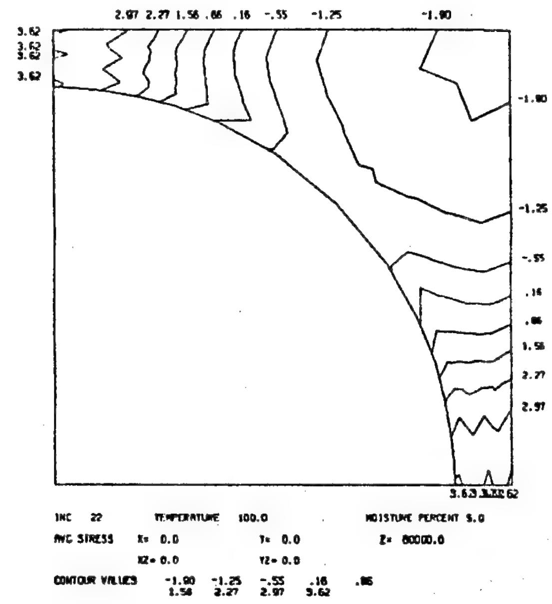
a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Interface Normal Stress (psi) d) Interface Shear Stress (psi)

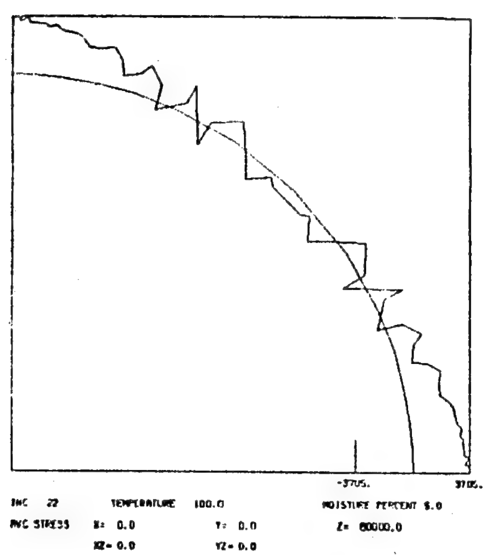
Figure E7. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, 5.0 Percent Moisture (RTW); 2.20 GPA (320 ksi) Longitudinal Tensile Applied Stress.



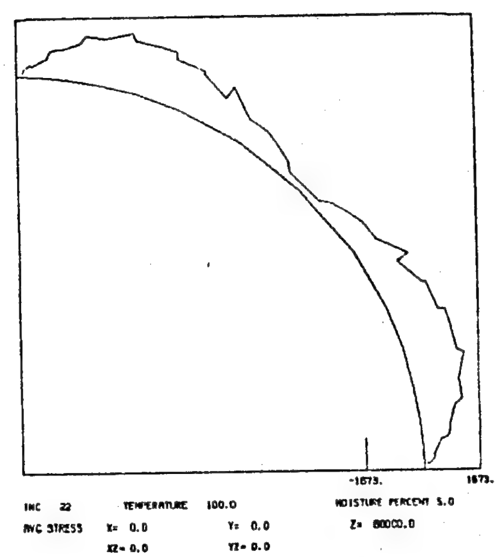
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

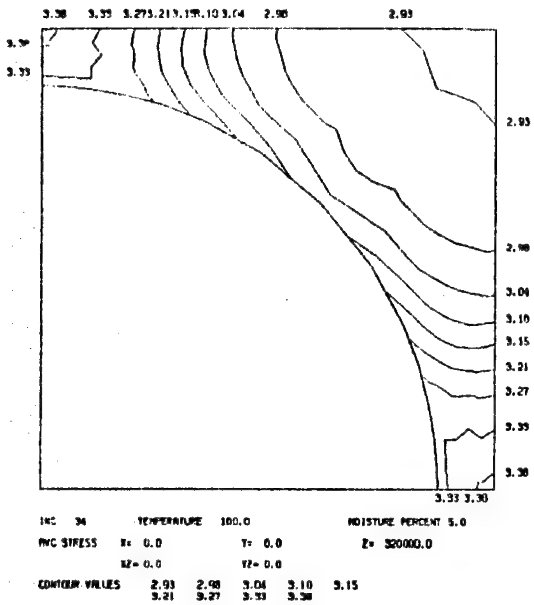


c) Interface Normal Stress (psi)

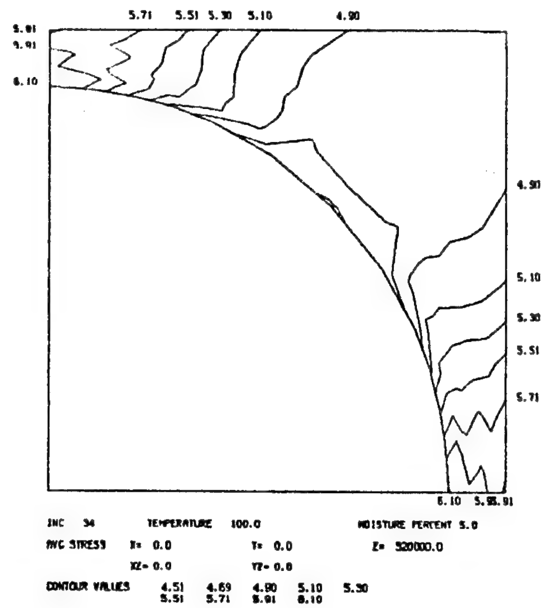


d) Interface Shear Stress (psi)

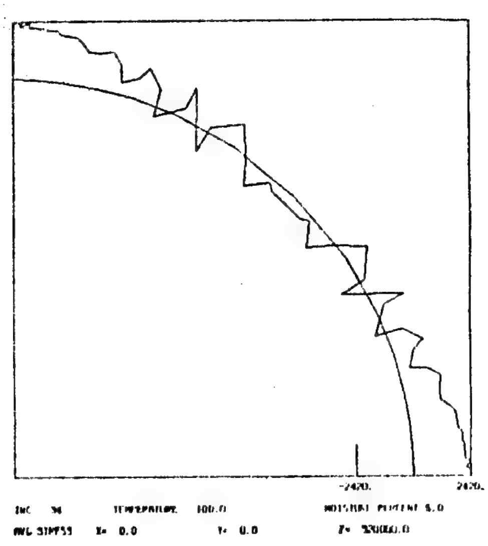
Figure E8. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 0.55 GPa (80 ksi) Longitudinal Tensile Applied Stress.



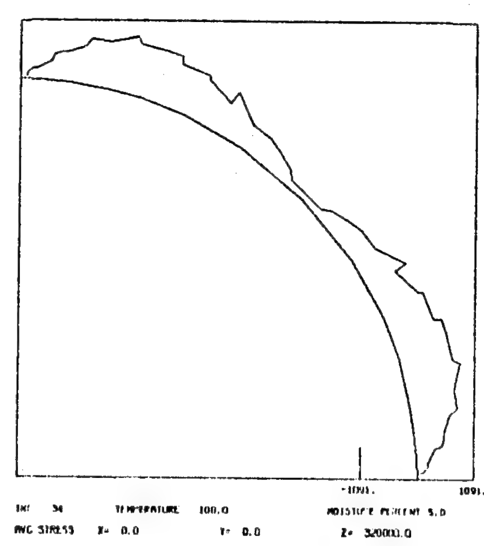
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

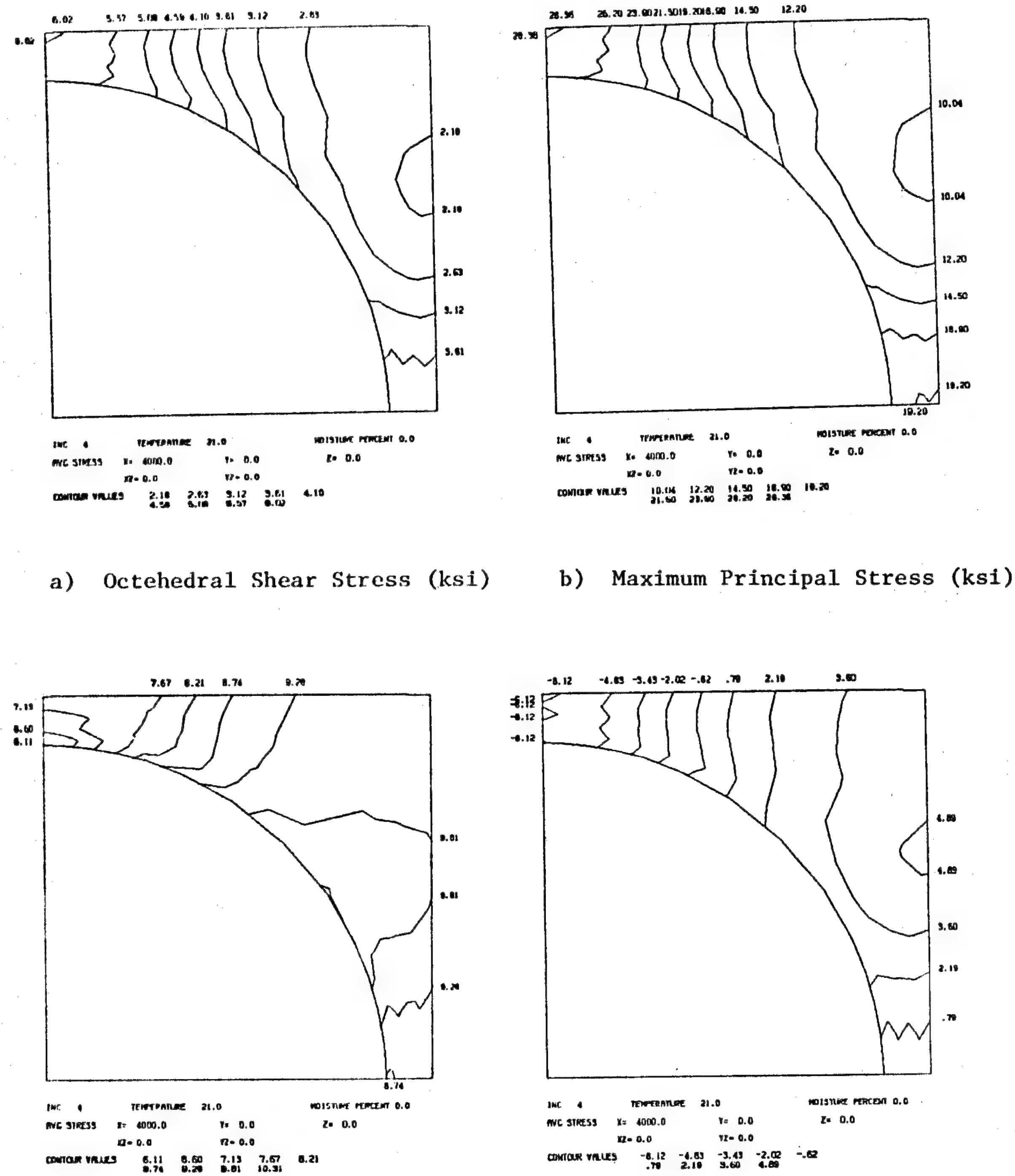


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

Figure E9. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



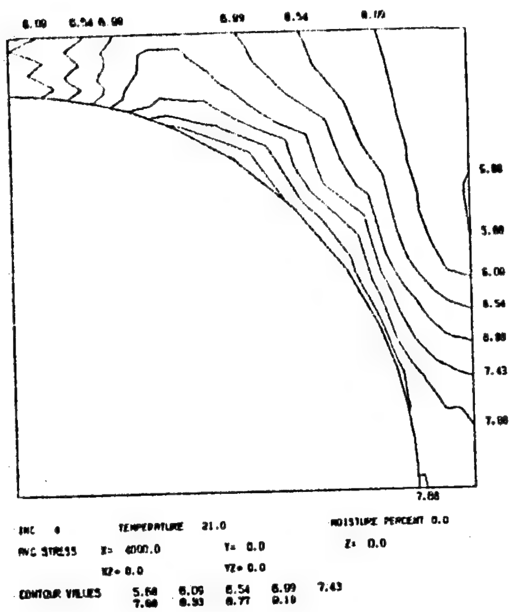
a) Octehedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

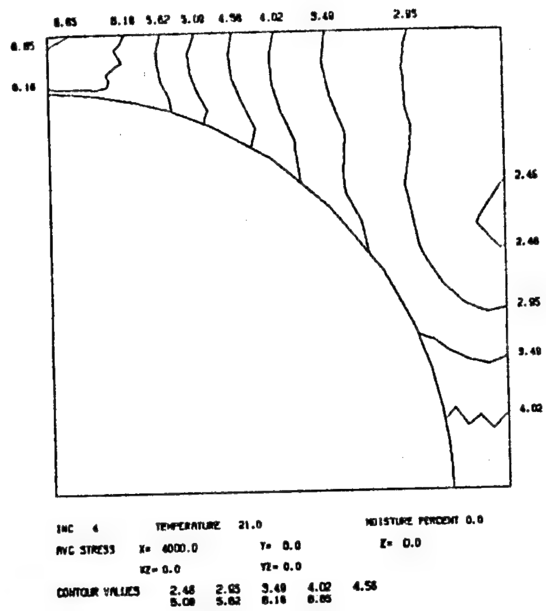
c) Minimum Principal Stress (ksi)

d) Intermediate Principal Stress (ksi)

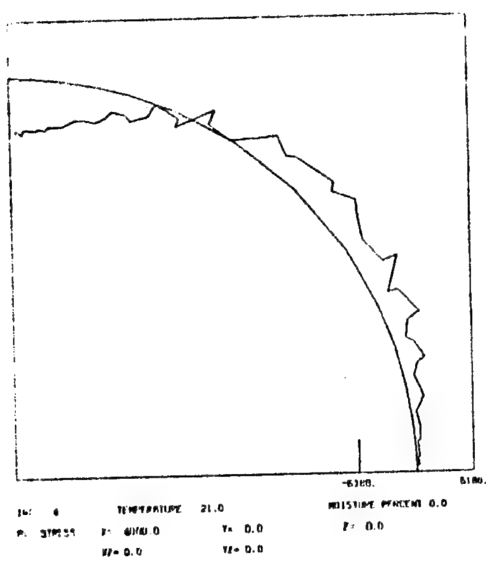
Figure E10. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



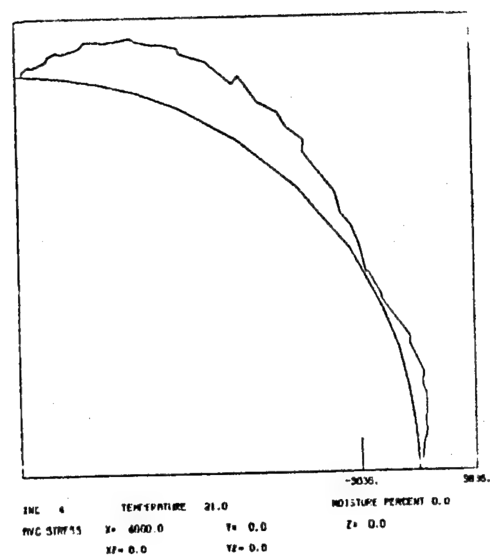
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

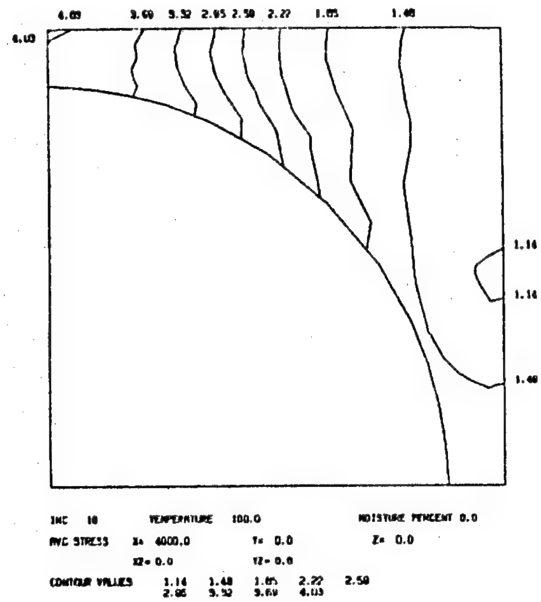


g) Interface Normal Shear (psi)

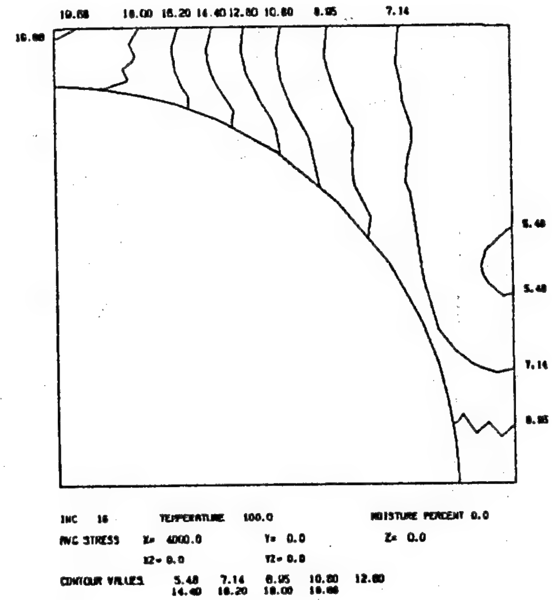


h) Interface Shear Stress (psi)

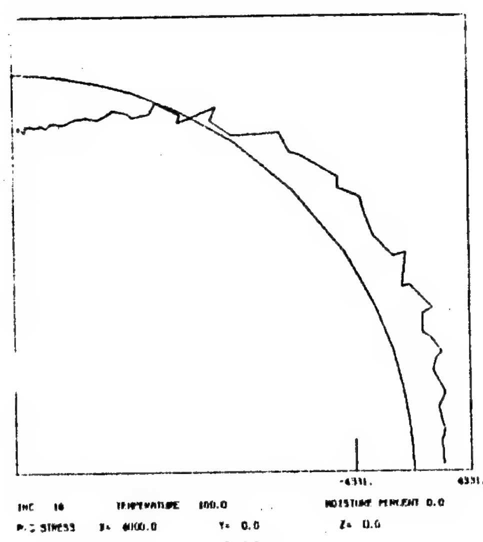
Figure E10 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



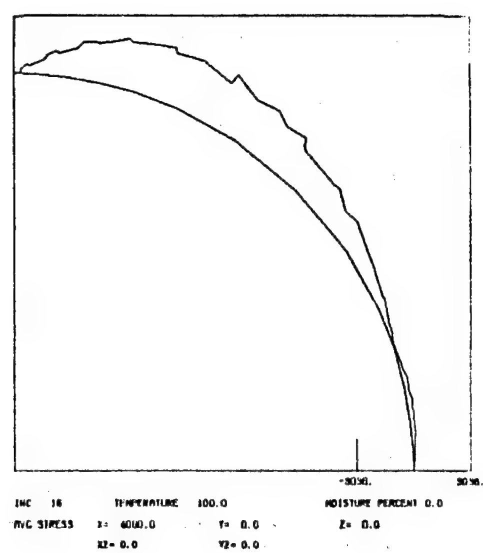
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

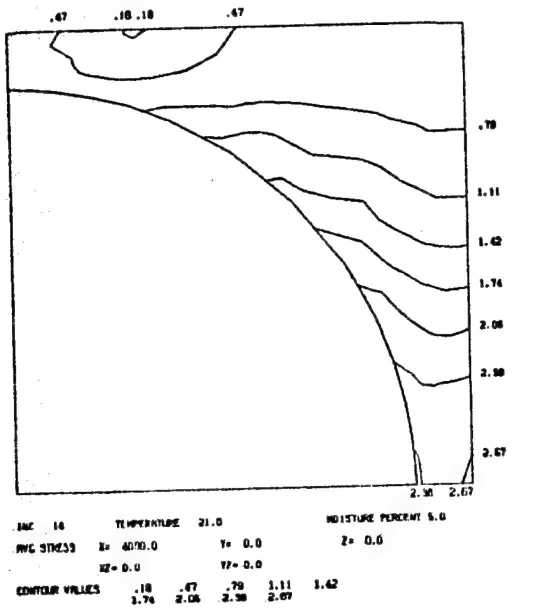


c) Interface Normal Stress (ksi)

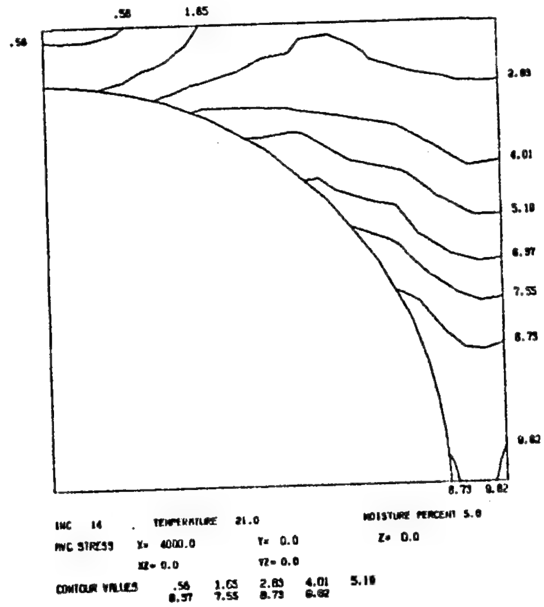


f) Interface Shear Stress (psi)

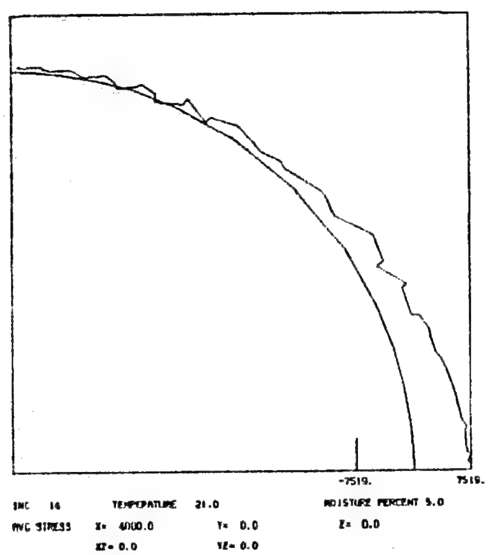
Figure E11. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



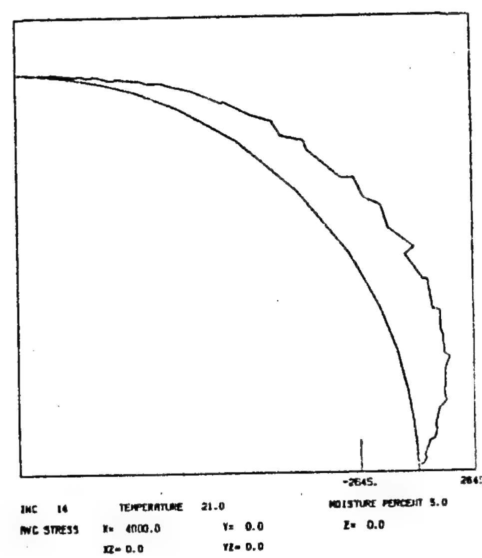
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

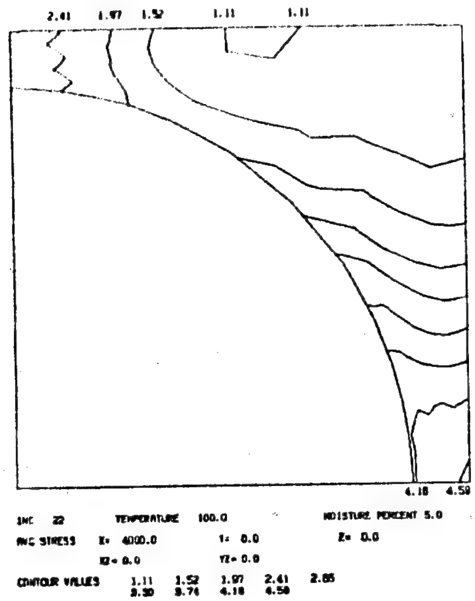


c) Interface Normal Stress (ksi)

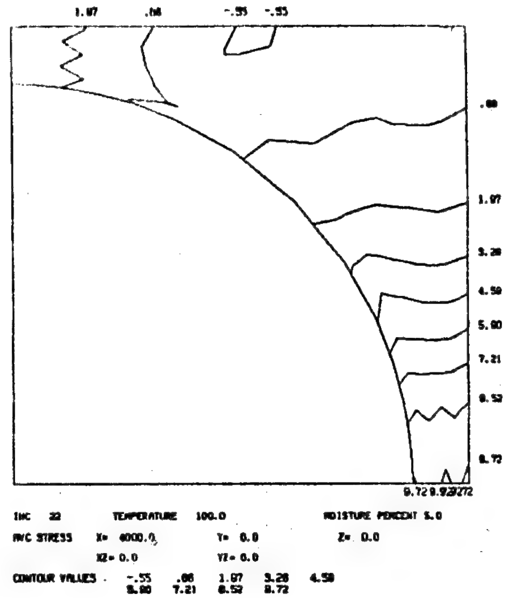


d) Interface Shear Stress (psi)

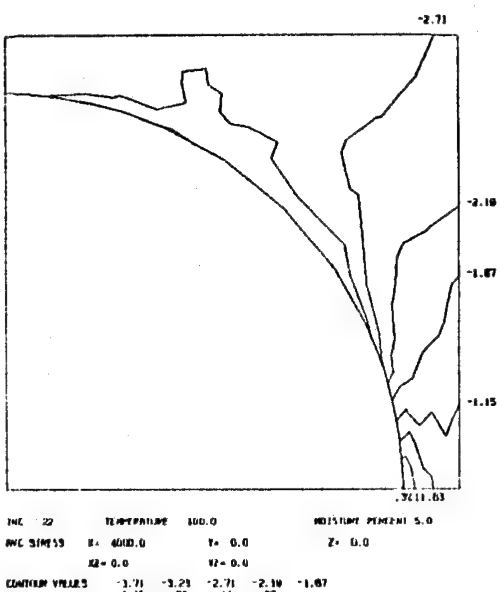
Figure E12. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, 5.0 Percent Moisture (RTW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



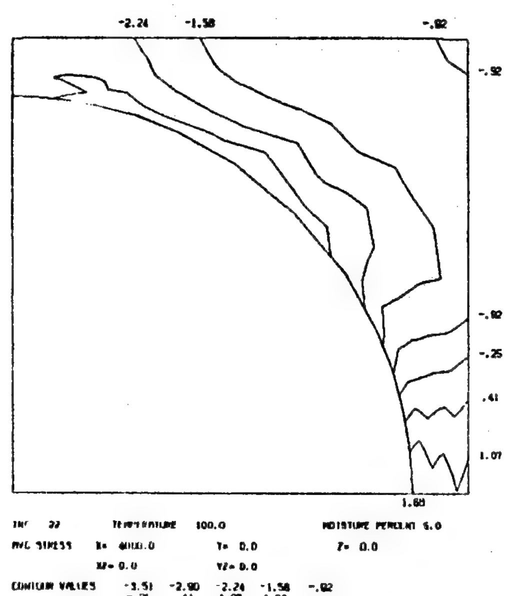
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

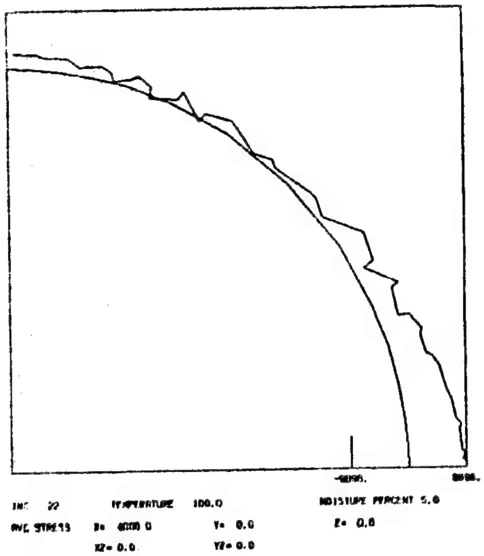


c) Minimum Principal Stress (ksi)

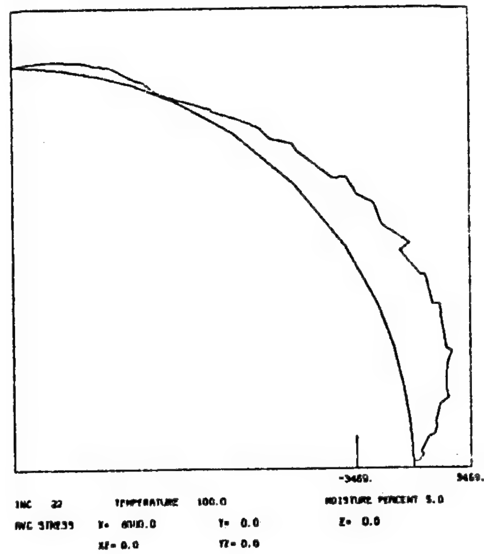


f) Intermediate Principal Stress (ksi)

Figure E13. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.

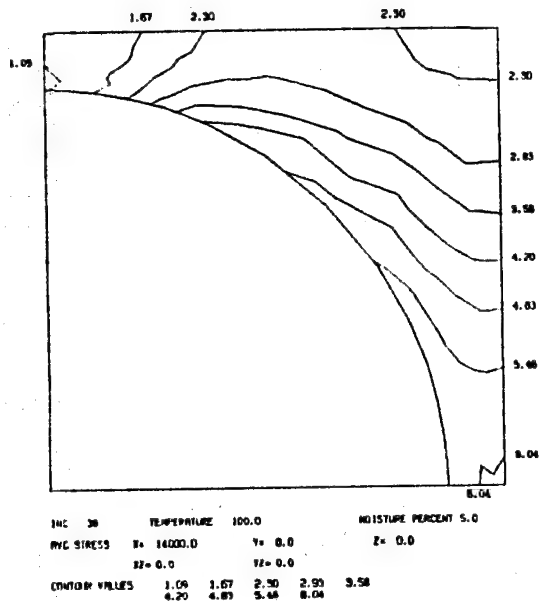


e) Interface Normal Stress (psi)

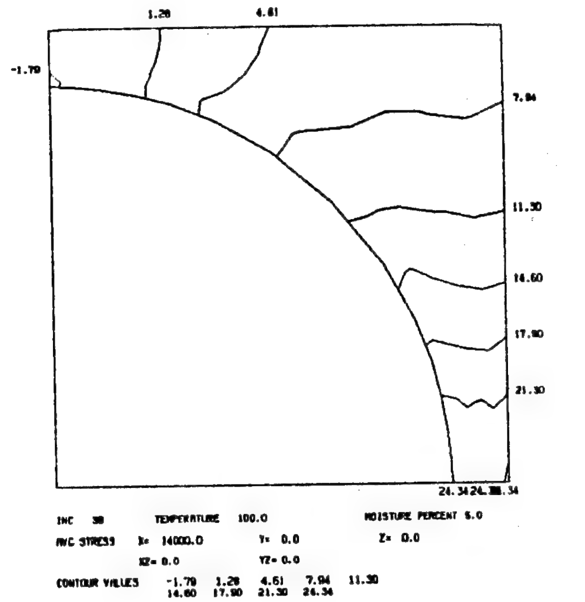


f) Interface Shear Stress (psi)

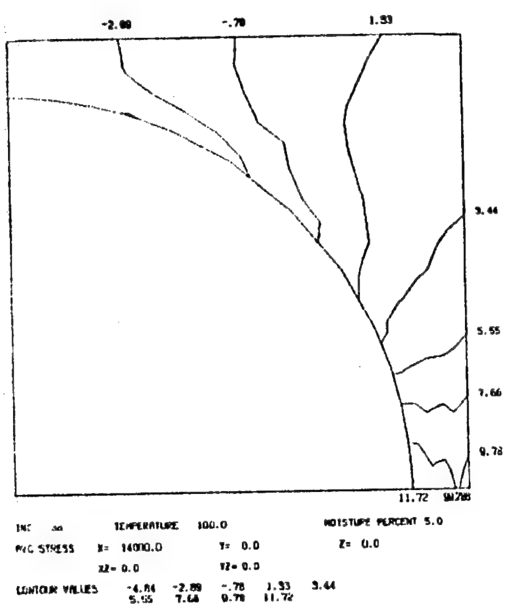
Figure E13 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



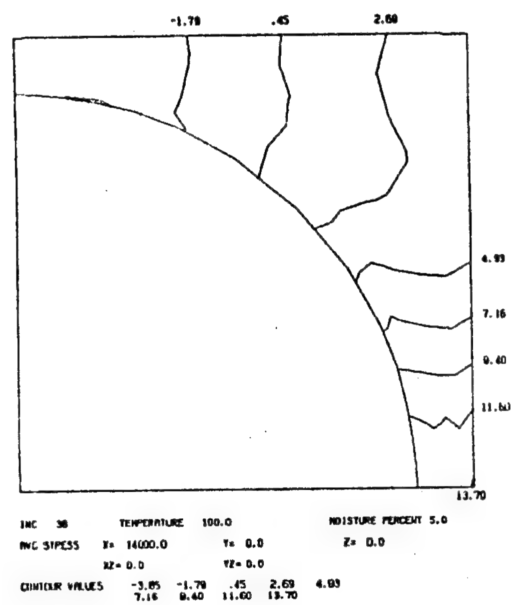
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

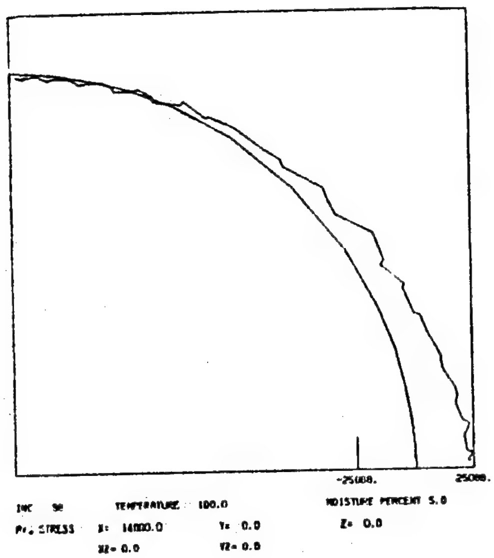


c) Minimum Principal Stress (ksi)

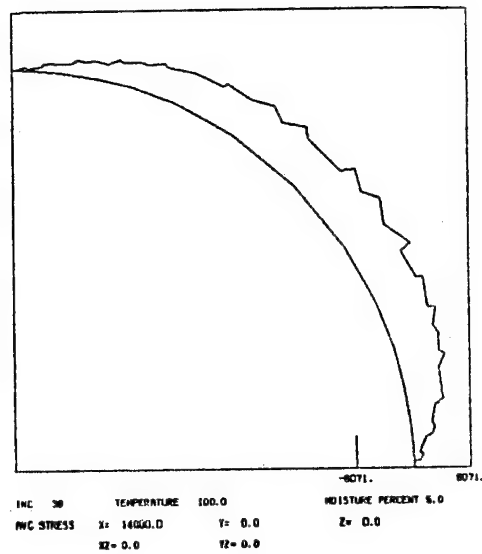


d) Intermediate Principal Stress (ksi)

Figure E14. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.

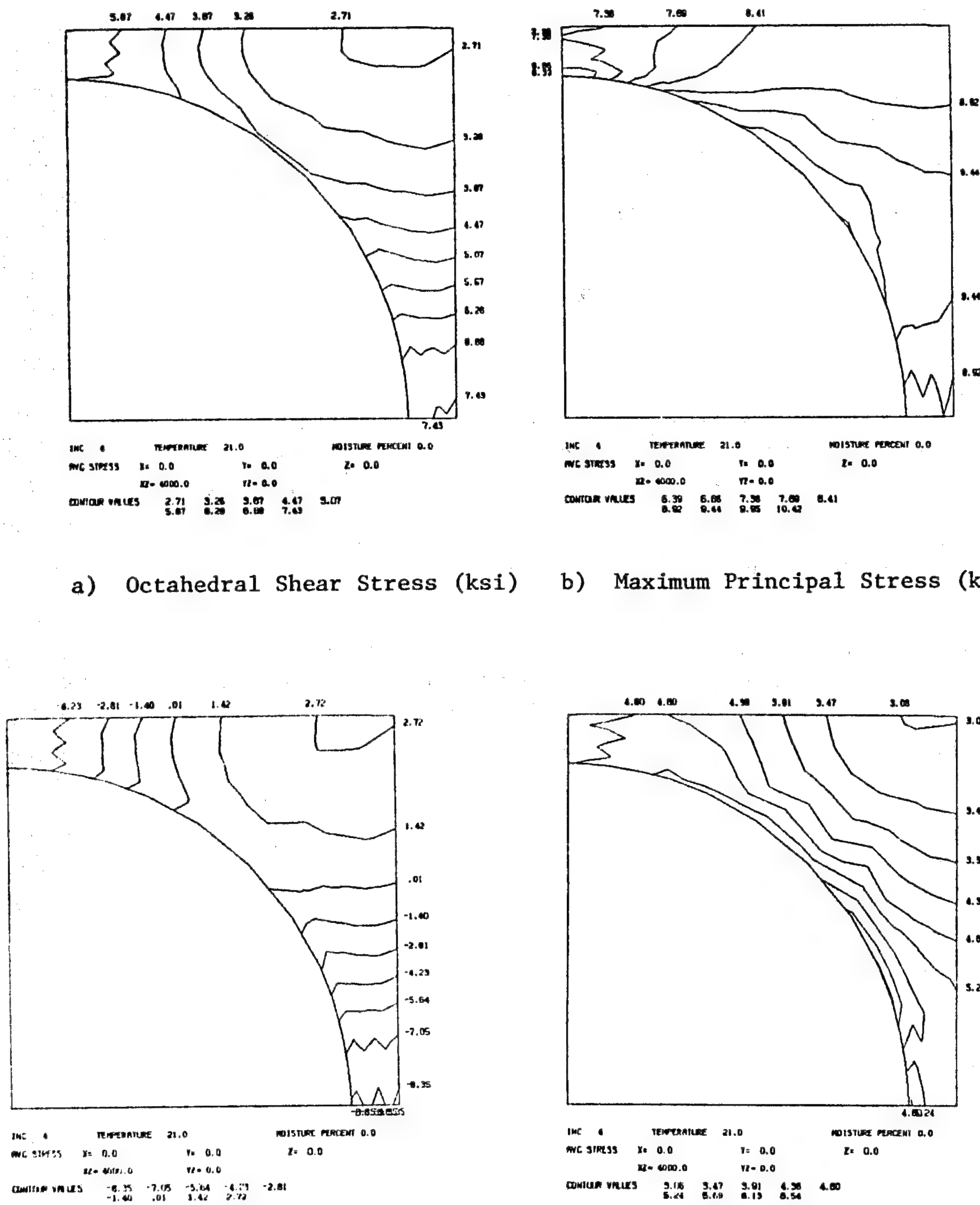


e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

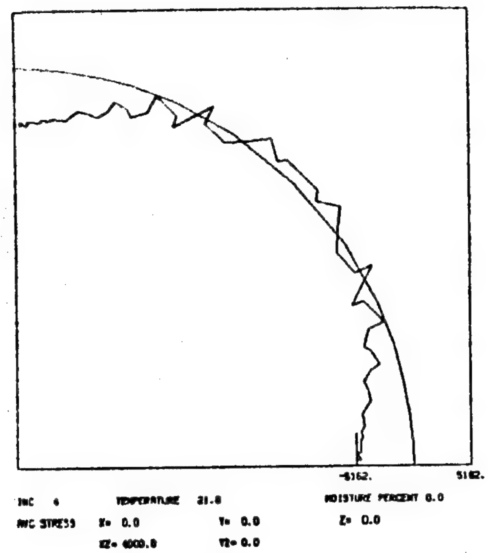
Figure E14 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.



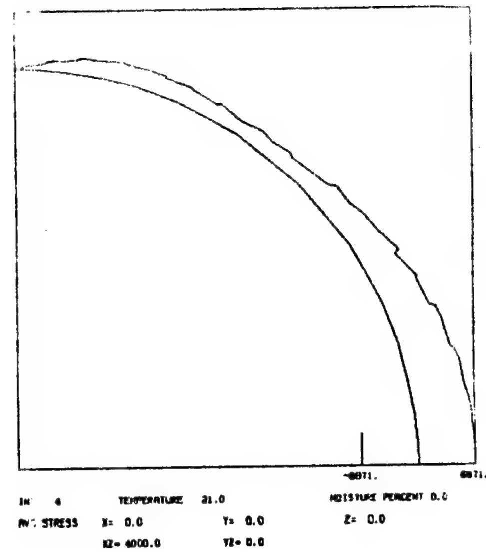
a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi) d) Intermediate Principal Stress (ksi)

Figure E15. AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

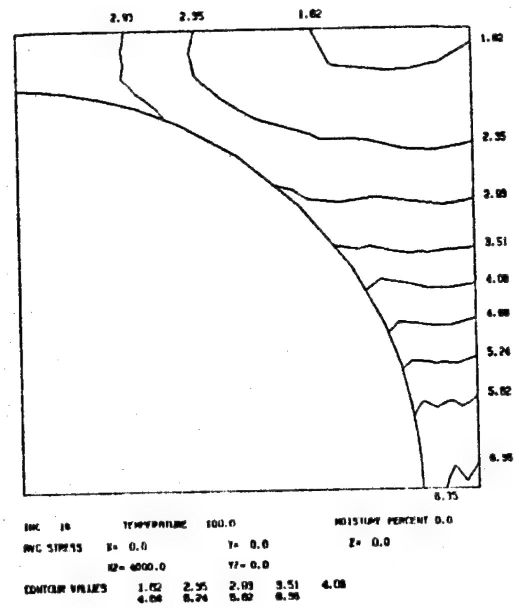


e) Interface Normal Stress (psi)

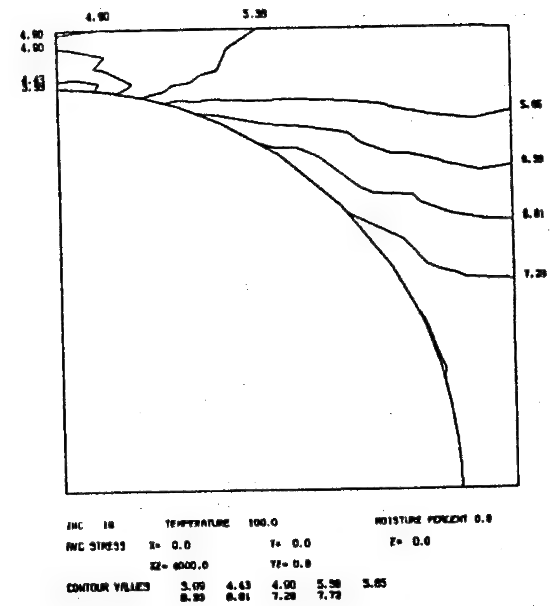


f) Interface Shear Stress (psi)

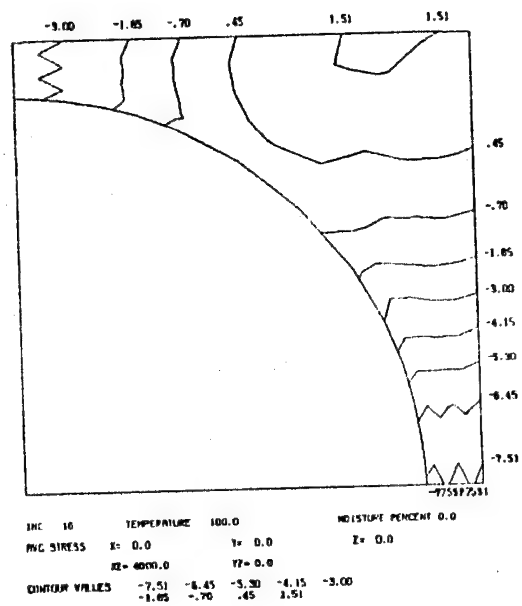
Figure E15 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



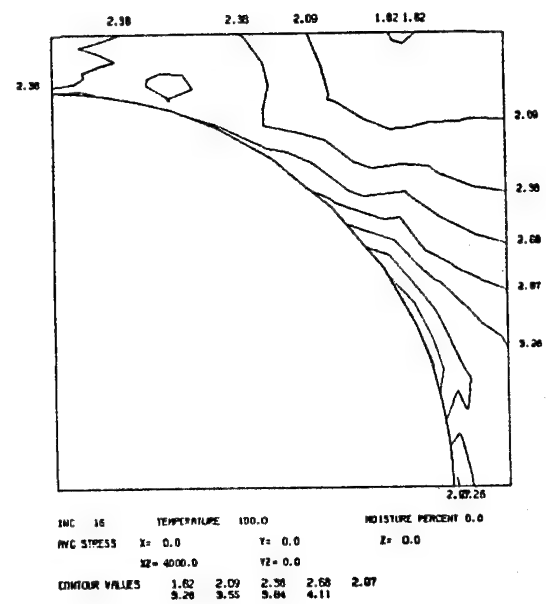
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

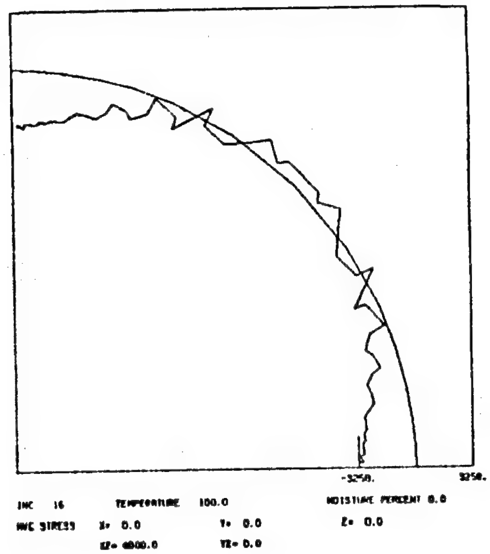


c) Minimum Principal Stress (ksi)

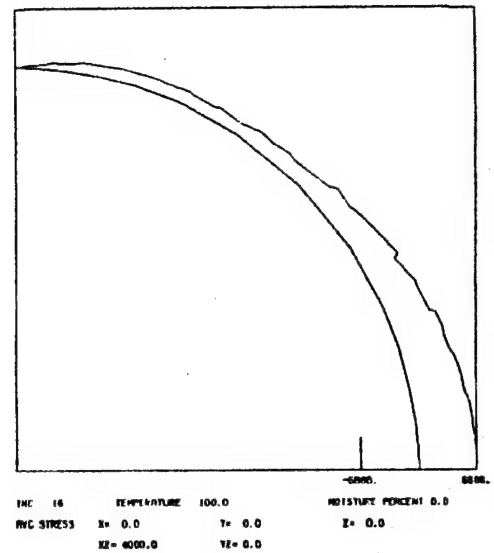


f) Intermediate Principal Stress (ksi)

Figure E16. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

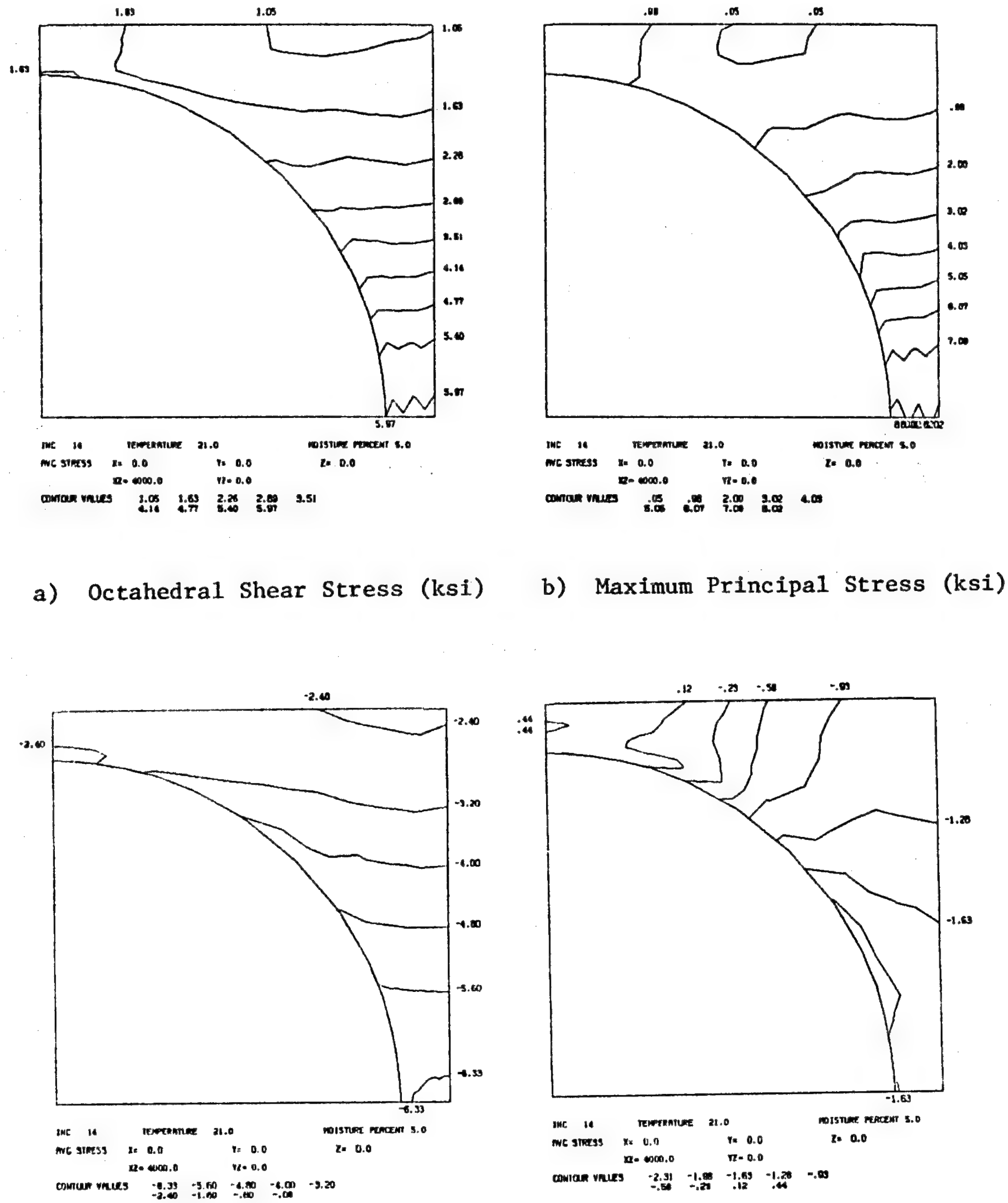


e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

Figure E16 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 100 °C,DRY (ETD);27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



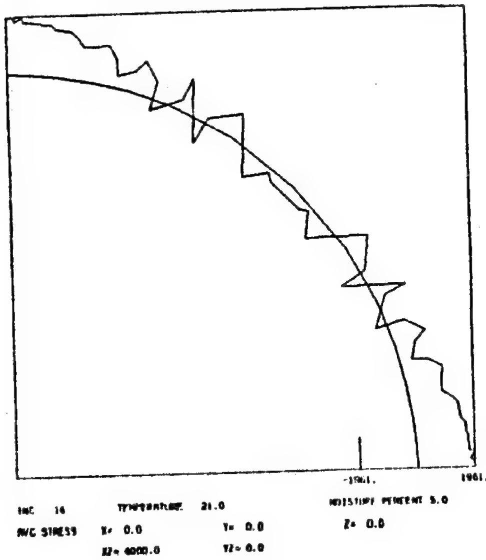
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

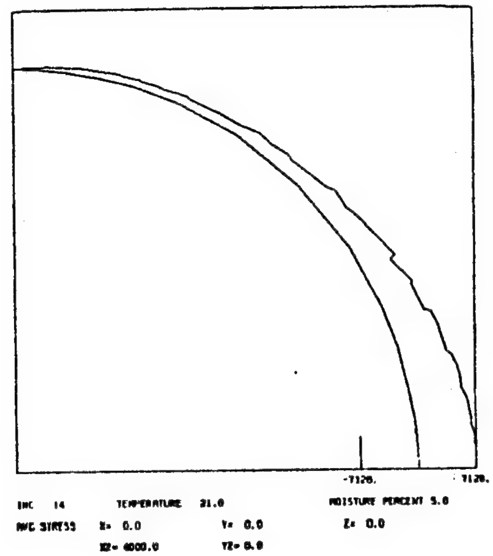
c) Minimum Principal Stress (ksi)

d) Intermediate Principal Stress (ksi)

Figure E17. AS4/3502 Graphite/Epoxy Unidirectional Composite, 21 ^{o}C, Wet (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

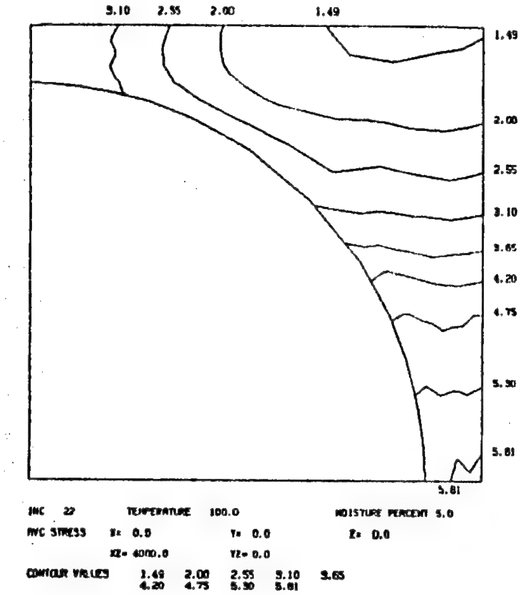


e) Interface Normal Stress (psi)

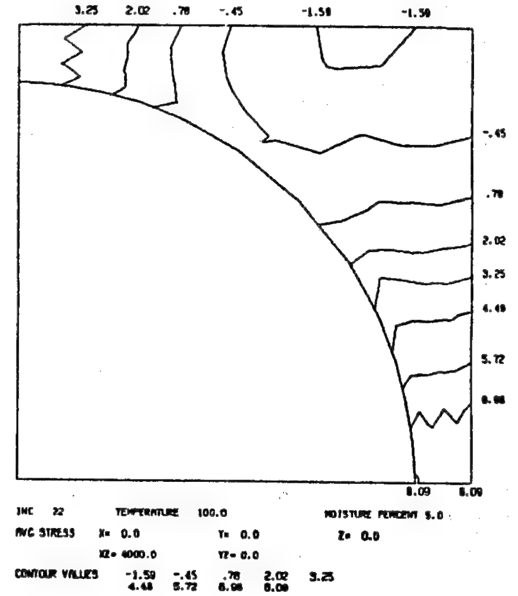


f) Interface Shear Stress (psi)

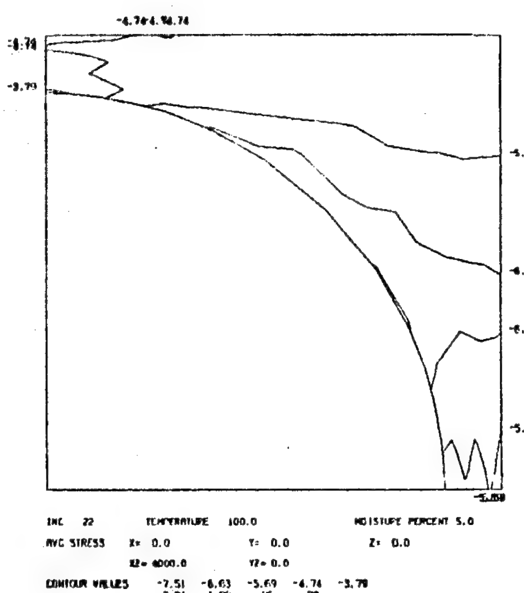
Figure E17 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 21^{o} C, Wet (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



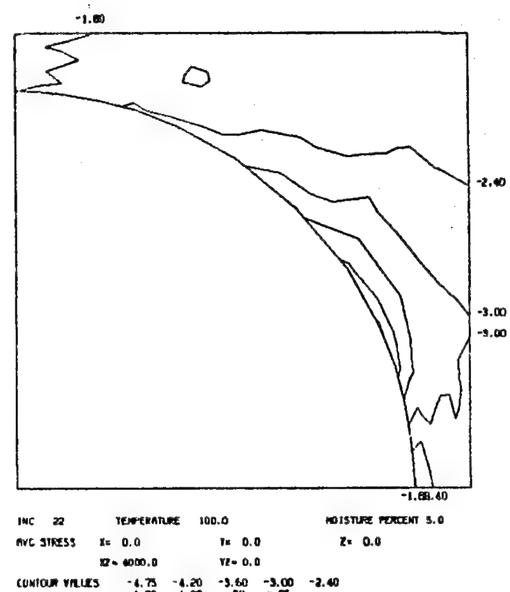
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

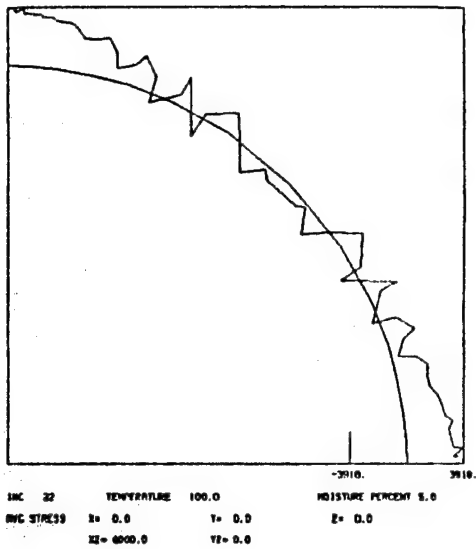


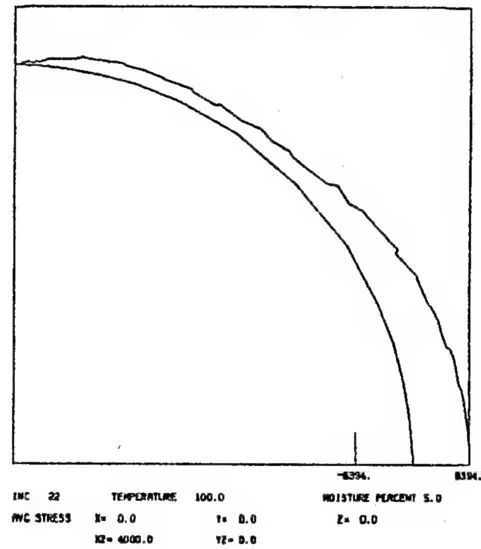
c) Minimum Principal Stress (ksi)



f) Intermediate Principal Stress (ksi)

Figure E18. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

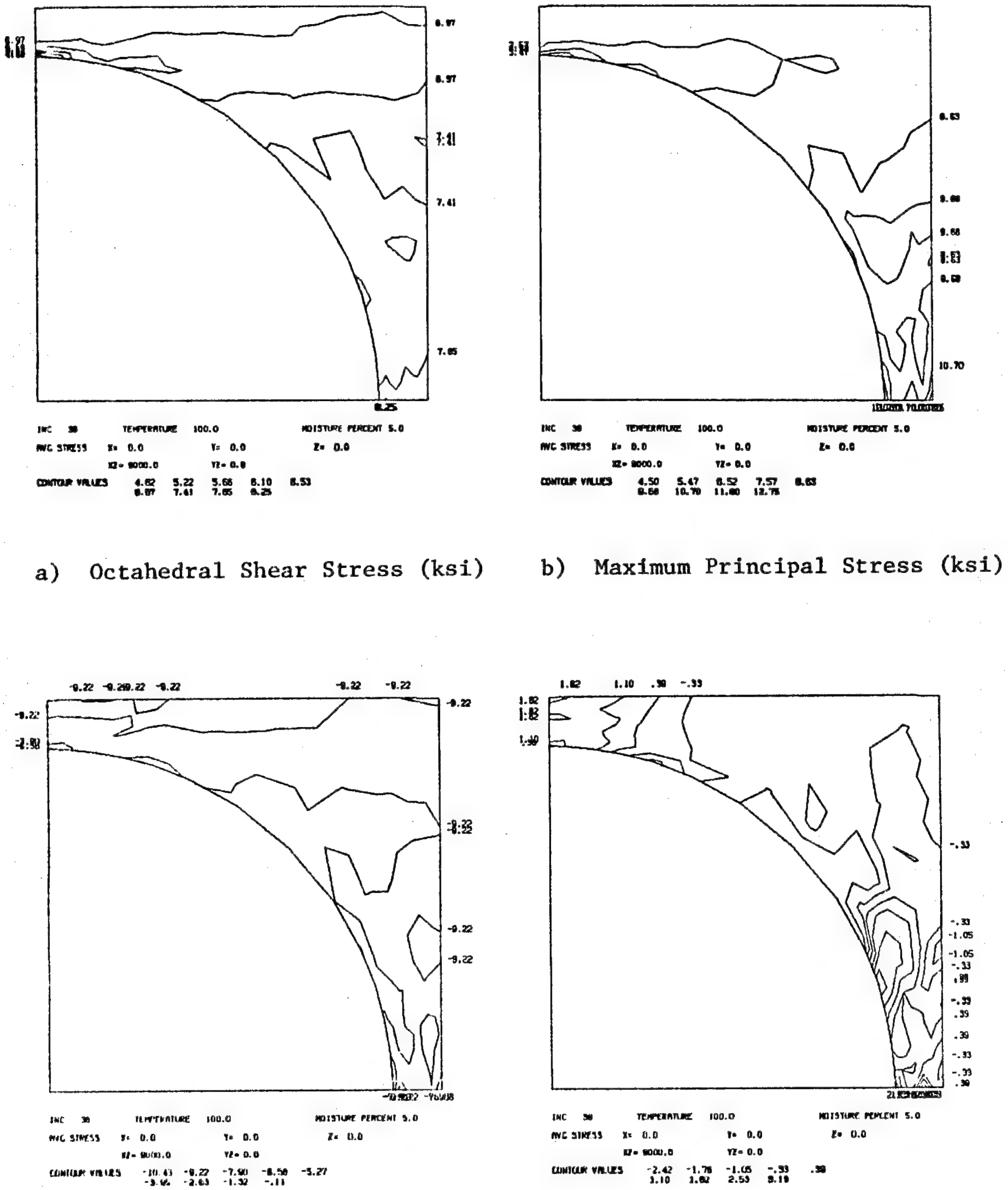




e) Interface Normal Stress (psi)

f) Interface Shear Stress (psi)

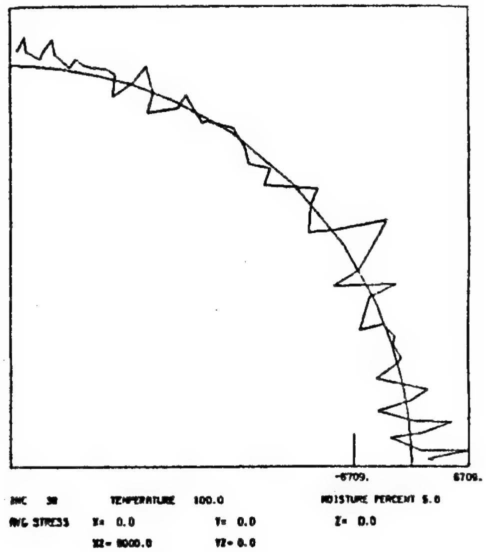
Figure E18 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



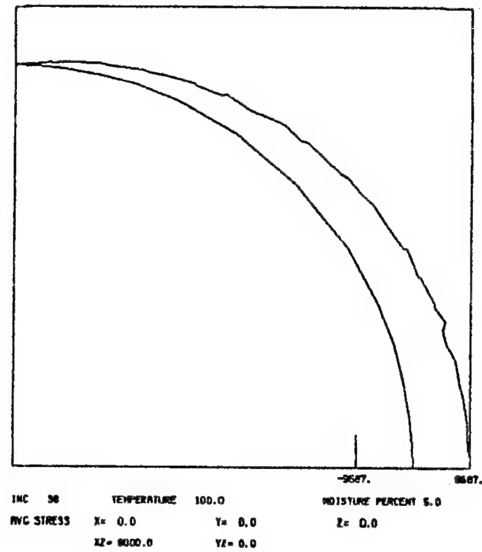
a) Octahedral Shear Stress (ksi)   b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi)   d) Intermediate Principal Stress (ksi)

Figure E19. AS4/3502 Graphite/Epoxy Unidirectional Composite, 100°C, 5.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.



e) Interface Normal Stress (psi)

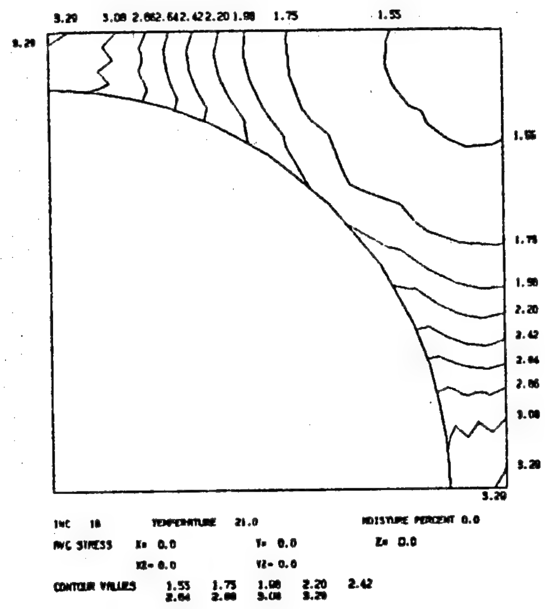


f) Interface Shear Stress (psi)

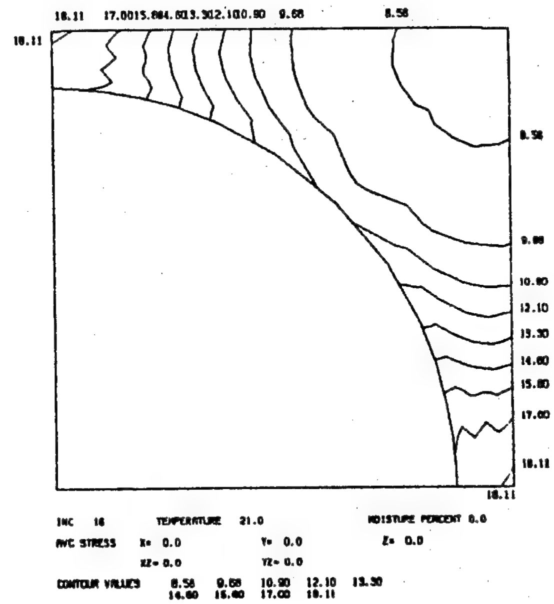
Figure E19 (continued). AS4/3502 Graphite/Epoxy Unidirectional Composite, $100^{o}C$, 5.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.

APPENDIX E2

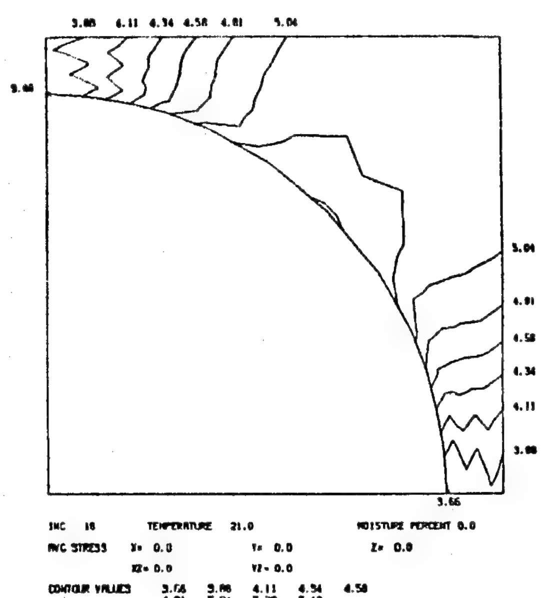
AS4/2220-3 GRAPHITE/EPOXY UNIDIRECTIONAL COMPOSITE



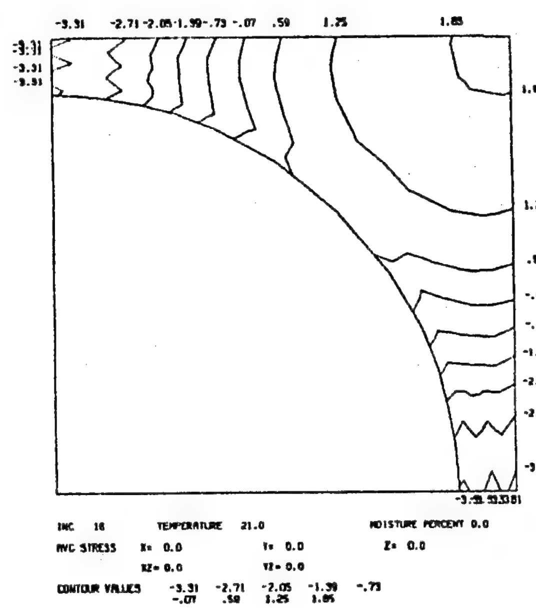
a) Octahedral Shear Stress (ksi)



b) Octahedral Shear Strain (10^{-3})

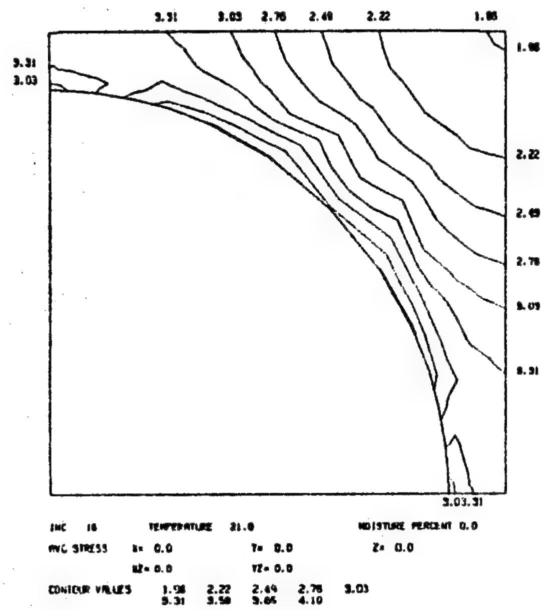


c) Maximum Principal Stress (ksi)

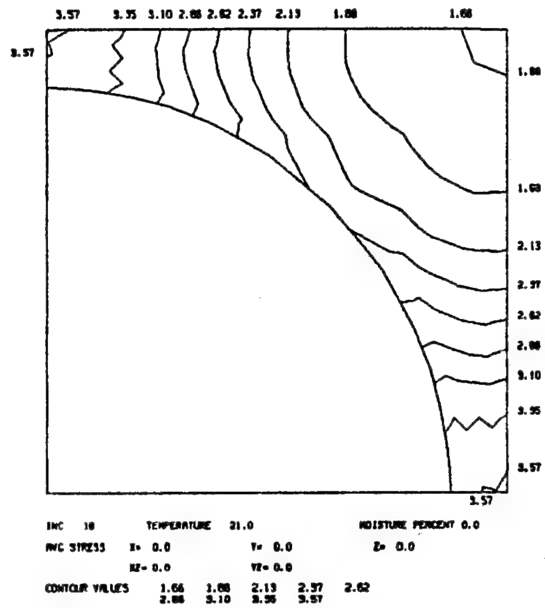


d) Minimum Principal Stress (ksi)

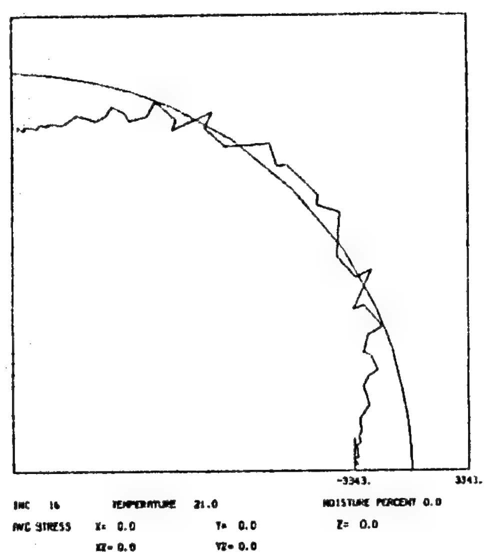
Figure E20. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



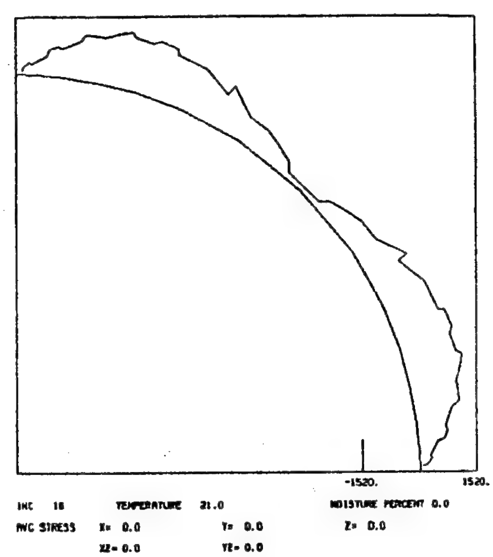
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

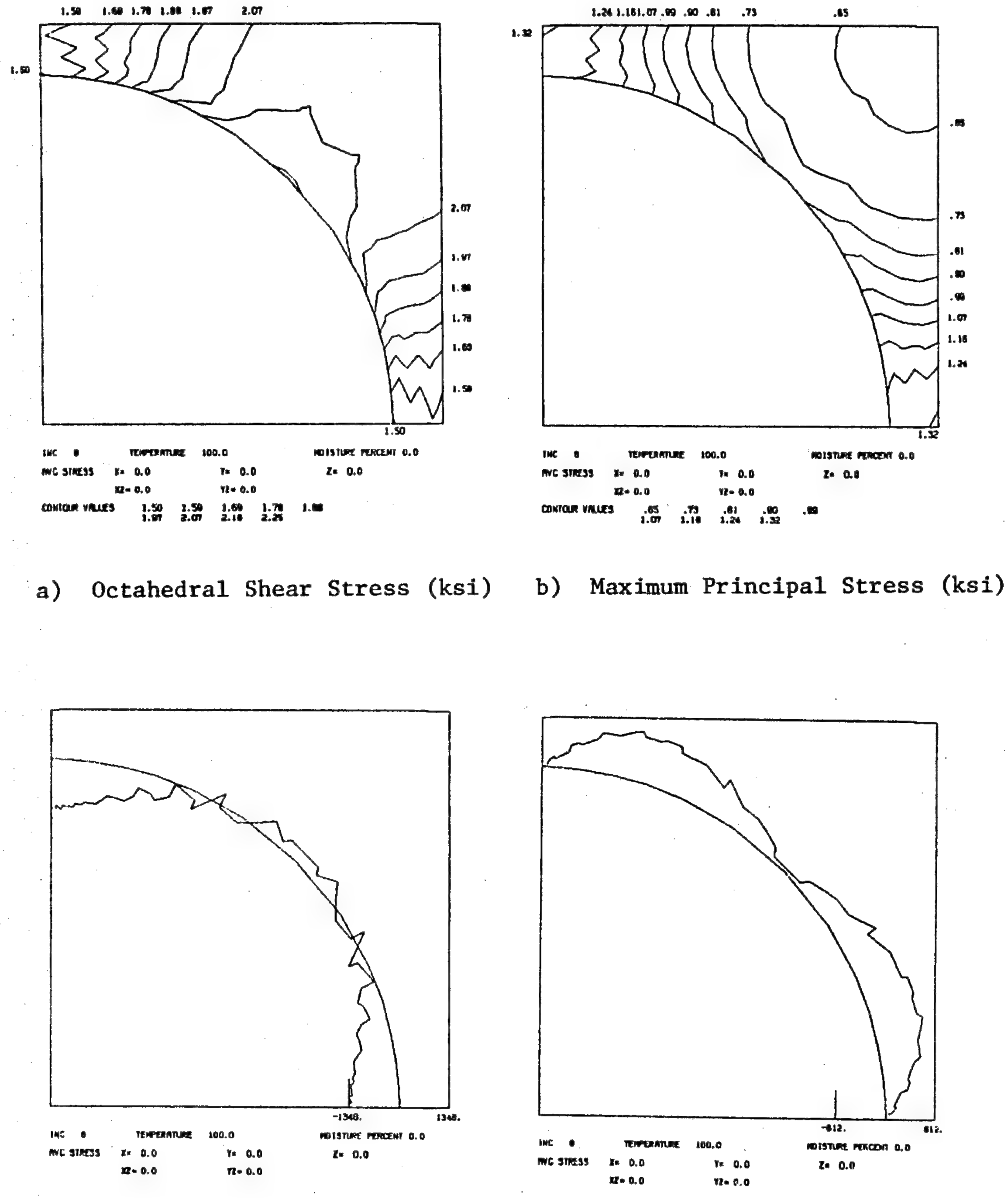


g) Interface Normal Stress (psi)



h) Interface Shear Stress (psi)

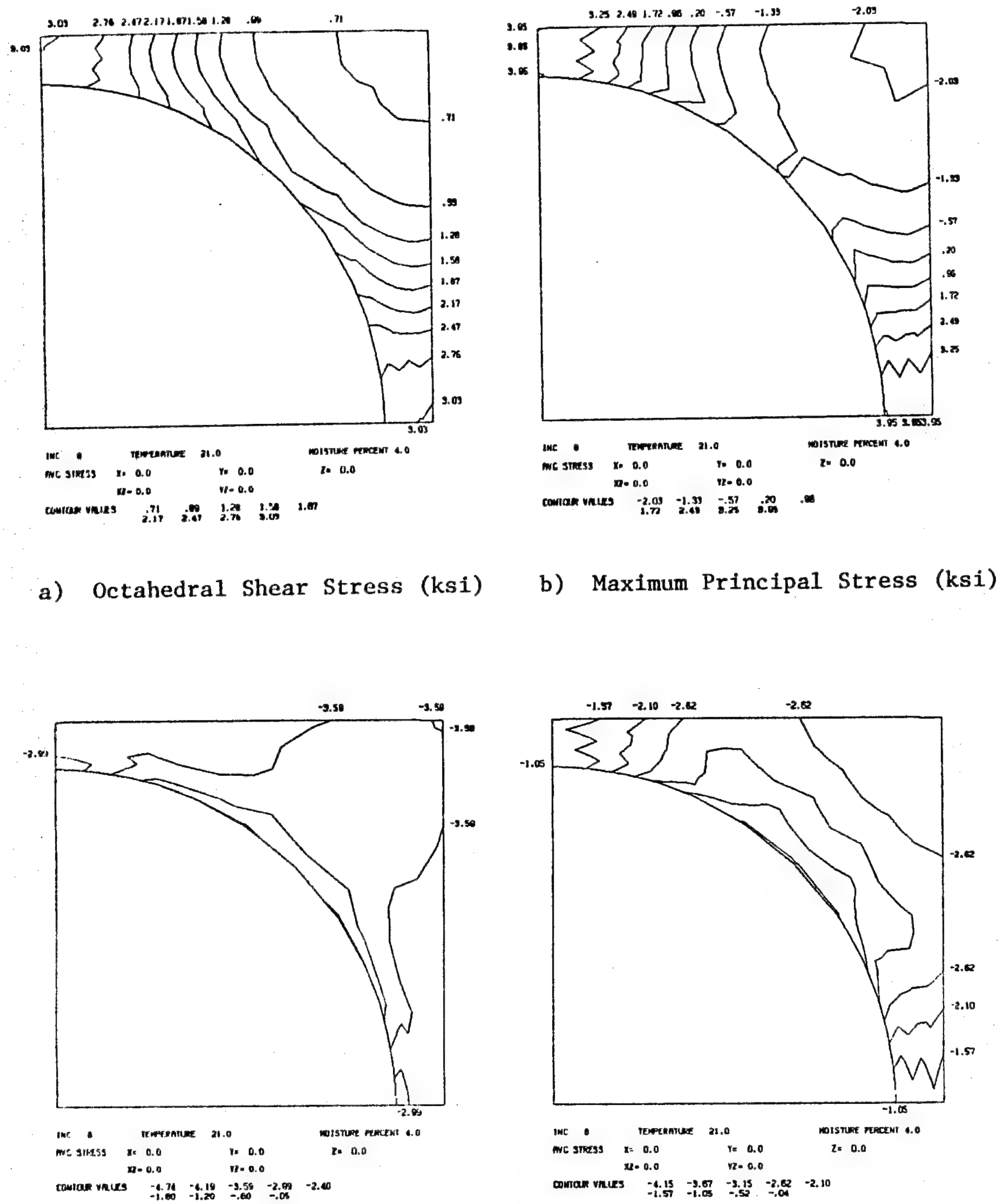
Figure E20 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Interface Normal Stress (psi) d) Interface Shear Stress (psi)

Figure E21. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, $100^{\circ}C$, Dry (ETD); No Mechanical Loading.



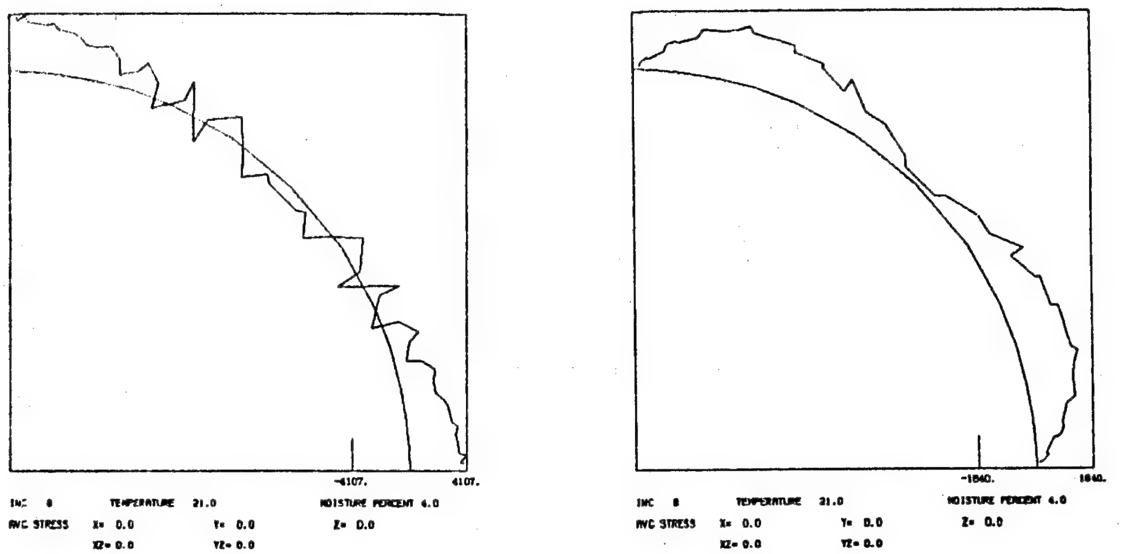
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

c) Maximum Principal Stress (ksi)

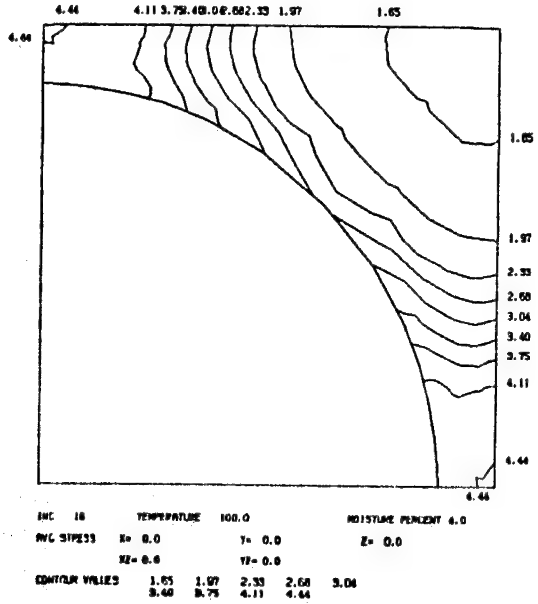
d) Intermediate Principal Stress (ksi)

Figure E22. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, 4.0 Percent Moisture (RTW); No Mechanical Loading.

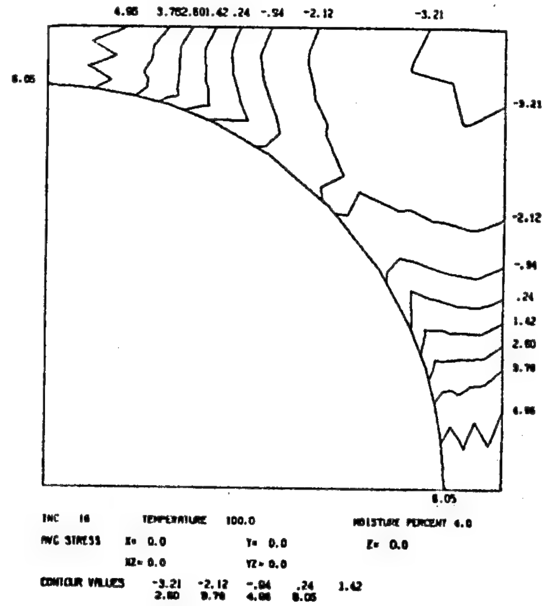


e) Interface Normal Stress (psi) f) Interface Shear Stress (psi)

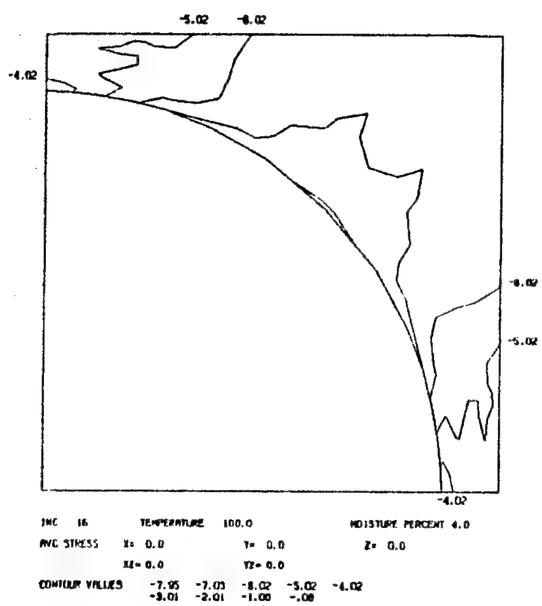
Figure E22 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, 4.0 Percent Moisture (RTW); No Mechanical Loading.



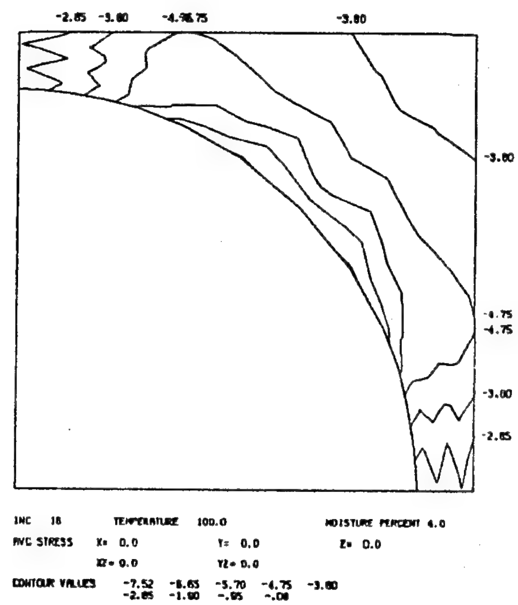
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

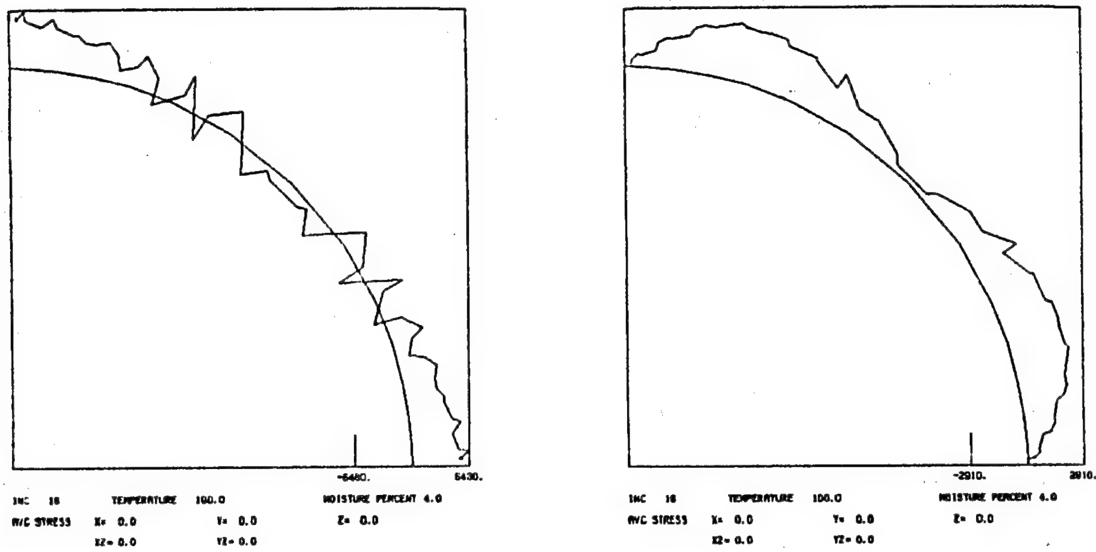


c) Minimum Principal Stress (ksi)



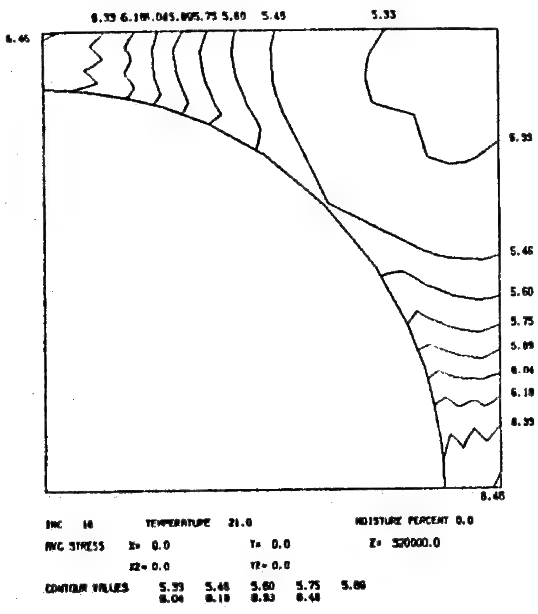
d) Intermediate Principal Stress (ksi)

Figure E23. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); No Mechanical Loading.

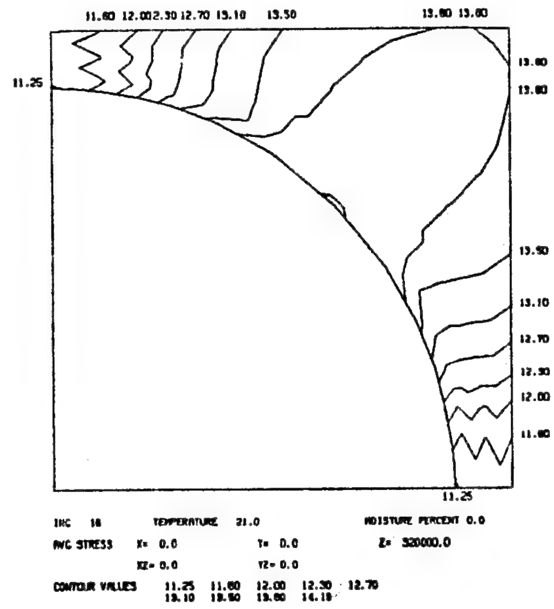


e) Interface Normal Stress (psi)   f) Interface Shear Stress (psi)

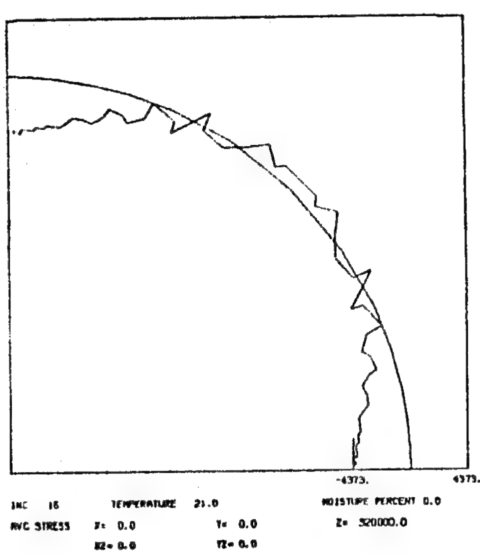
Figure E23 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); No Mechanical Loading.



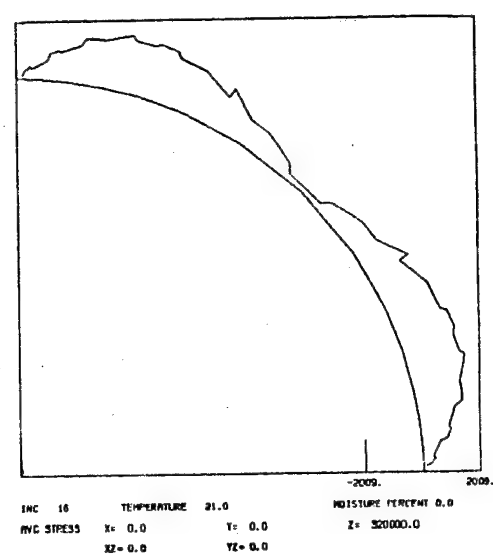
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

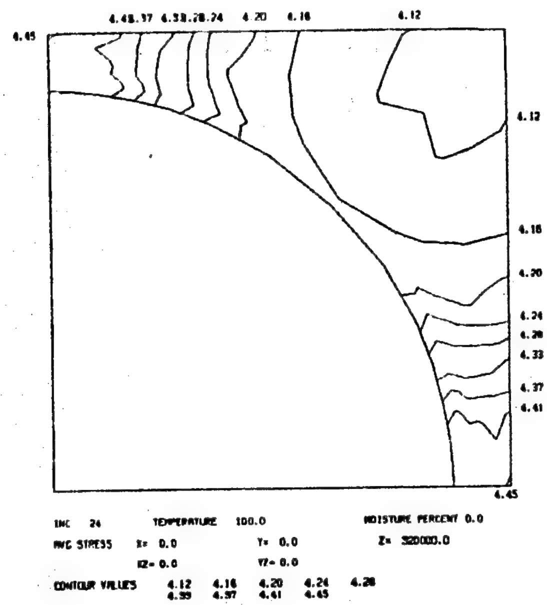


c) Interface Normal Stress (psi)

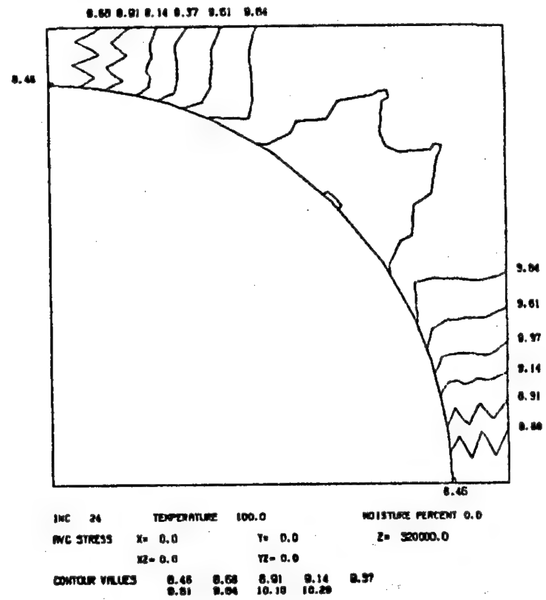


d) Interface Shear Stress (psi)

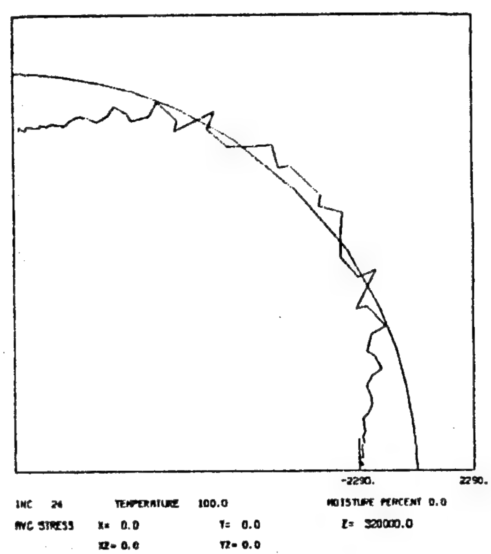
Figure E24. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



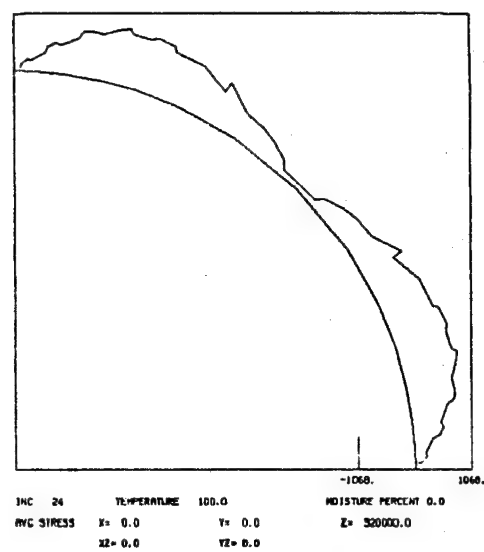
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

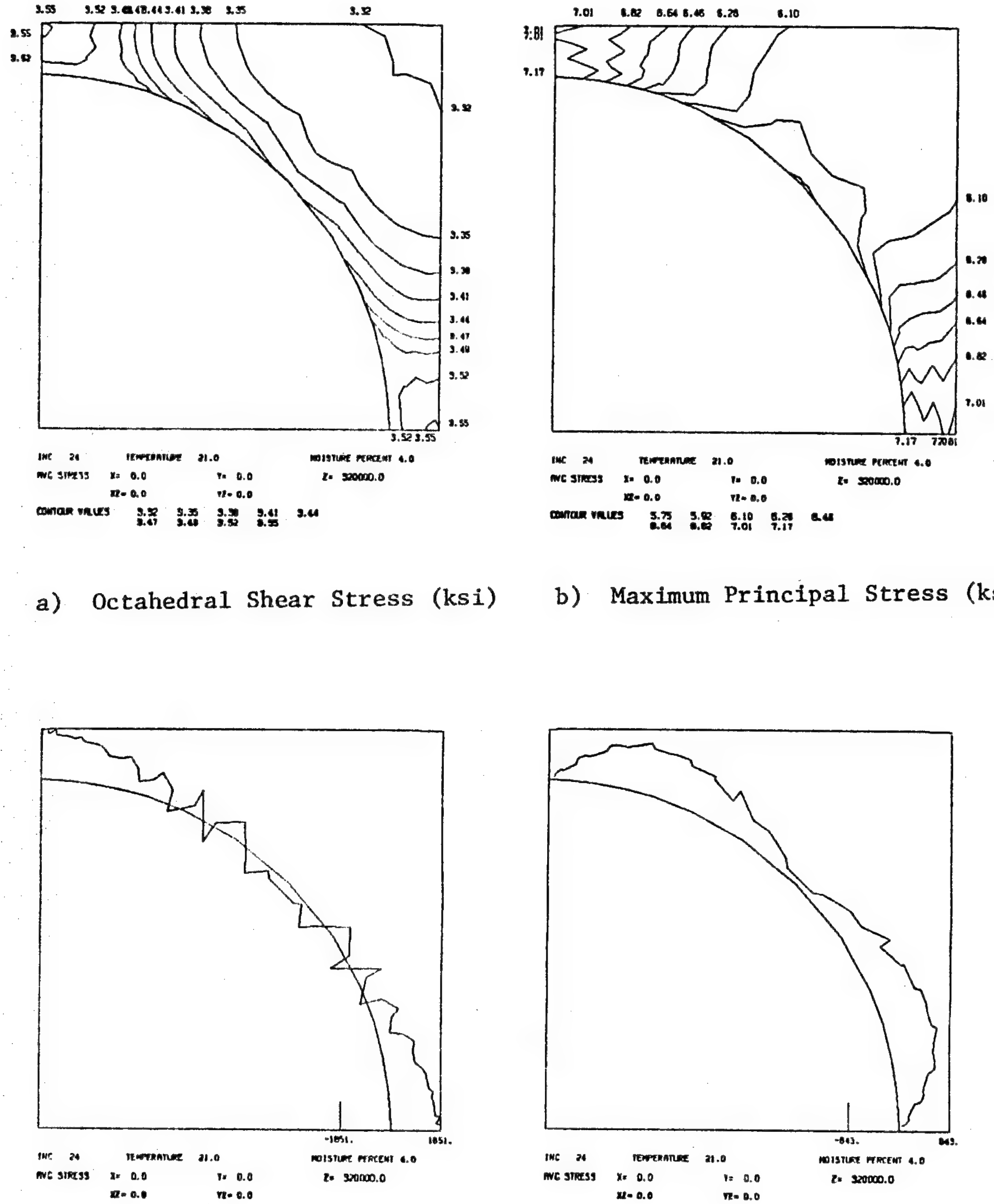


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

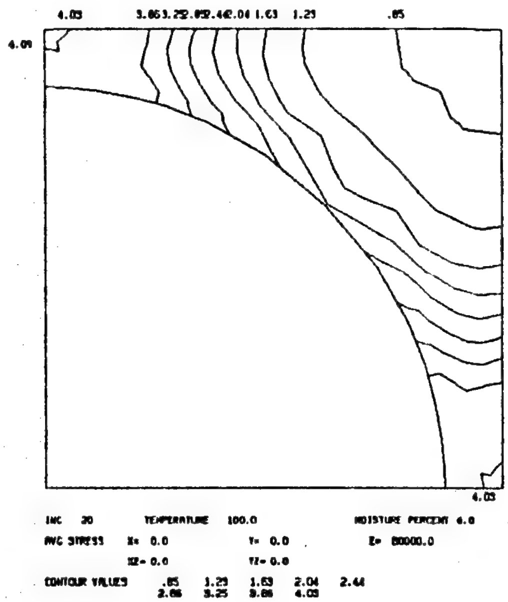
Figure E25. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



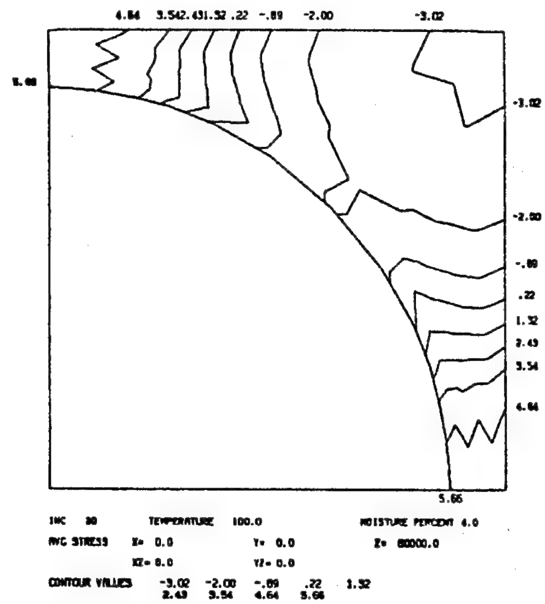
a) Octahedral Shear Stress (ksi)   b) Maximum Principal Stress (ksi)

c) Interface Normal Stress (psi)   d) Interface Shear Stress (psi)

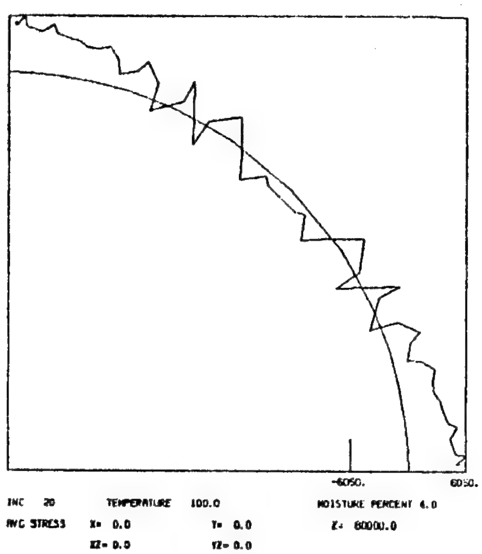
Figure E26. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, 4.0 Percent Moisture (RTW); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



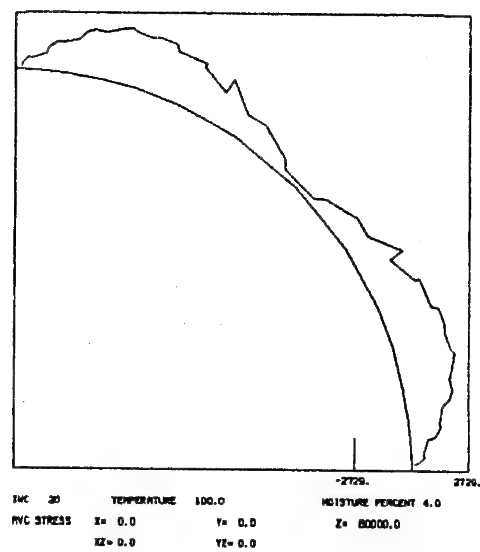
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

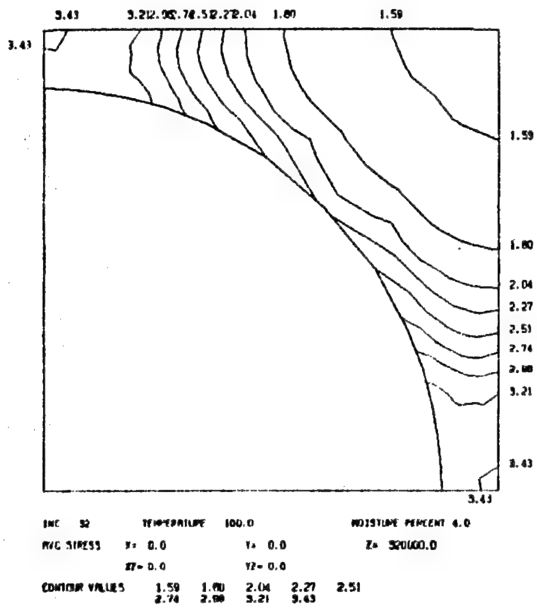


c) Interface Normal Stress (psi)

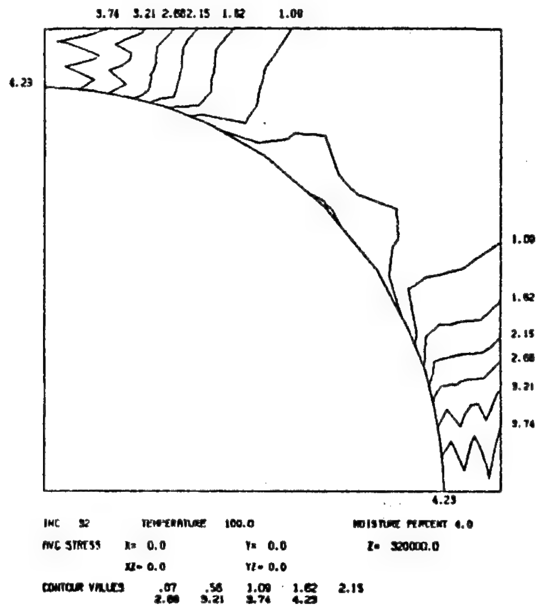


d) Interface Shear Stress (psi)

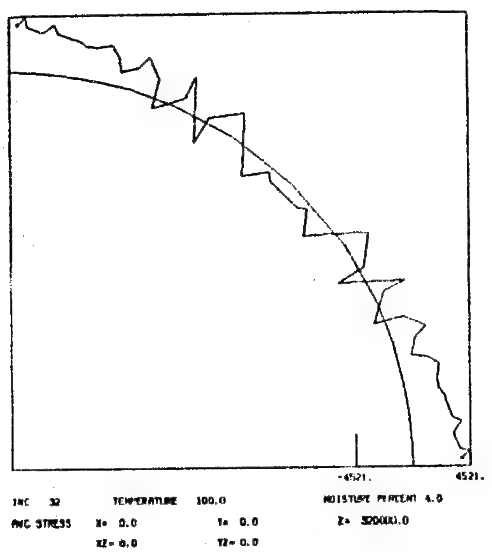
Figure E27. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, $100^{\circ}C$, 4.0 Percent Moisture (ETW); 0.55 GPa (80 ksi) Longitudinal Tensile Applied Stress.



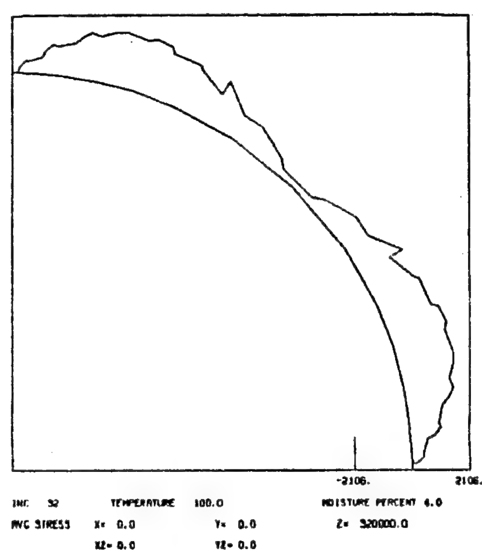
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

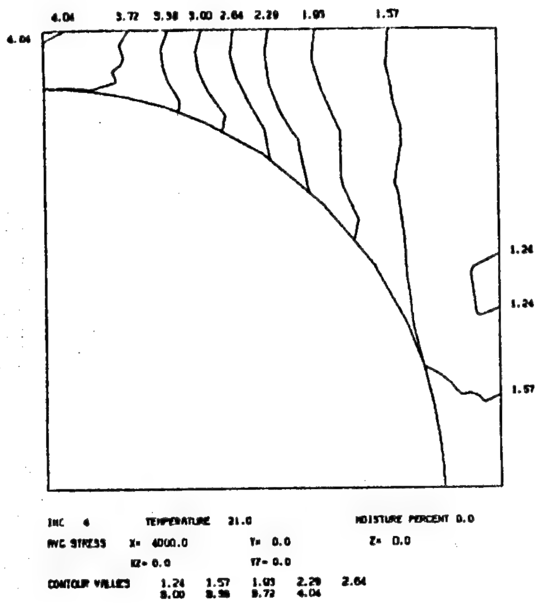


c) Interface Normal Stress (psi)

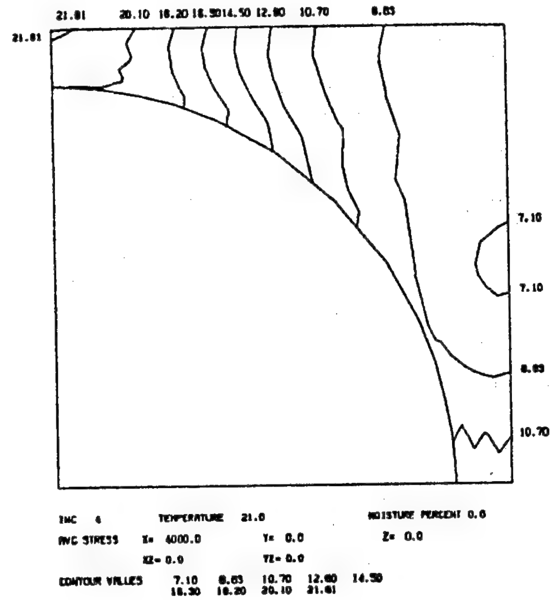


d) Interface Shear Stress (psi)

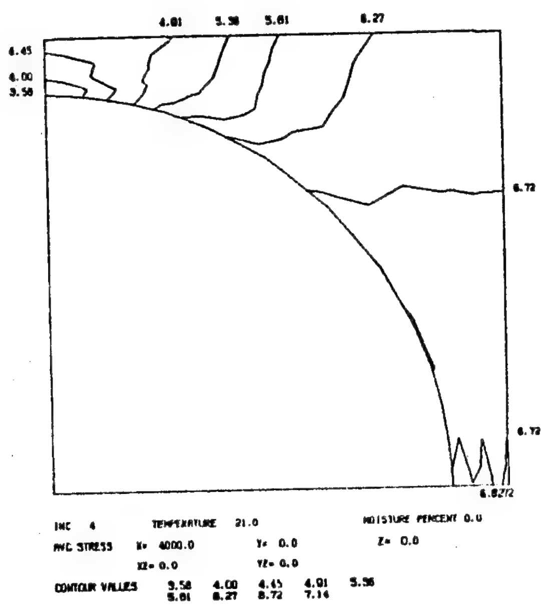
Figure E28. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C 4.0 Percent Moisture (ETW); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



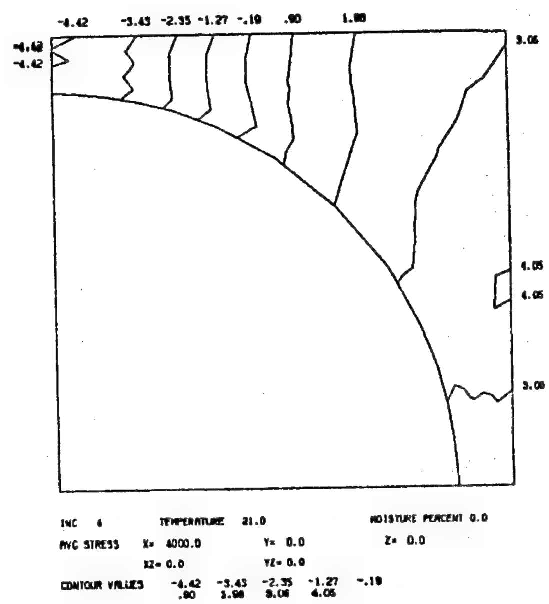
a) Octehedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

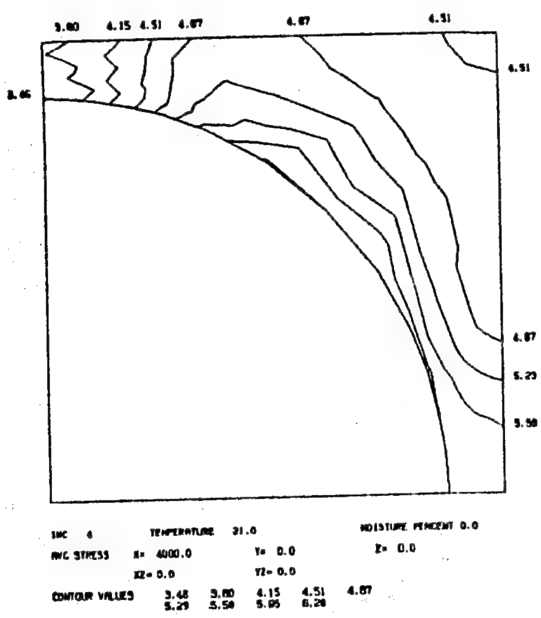


c) Minimum Principal Stress (ksi)

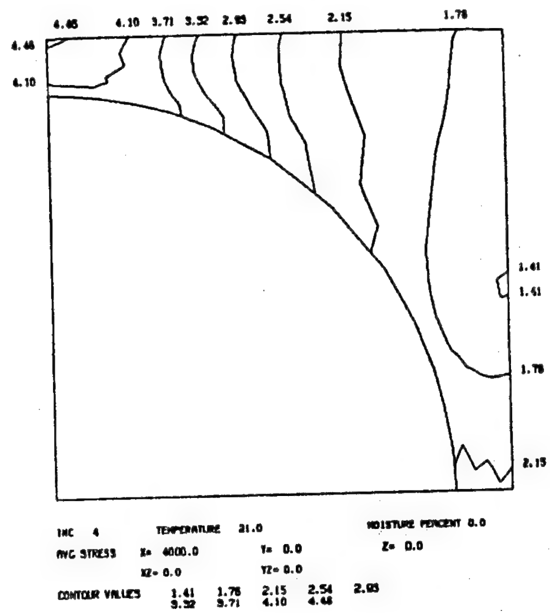


d) Intermediate Principal Stress (ksi)

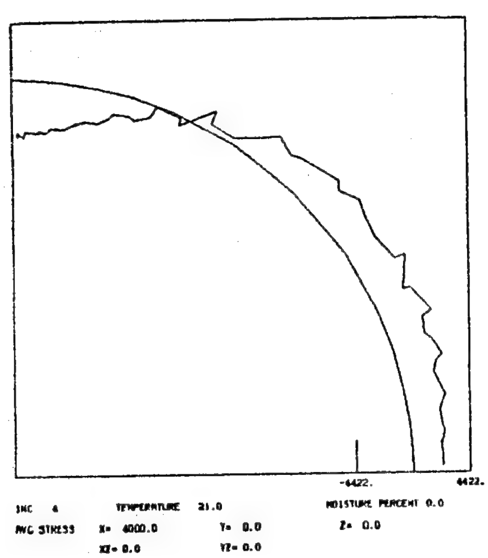
Figure E29. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



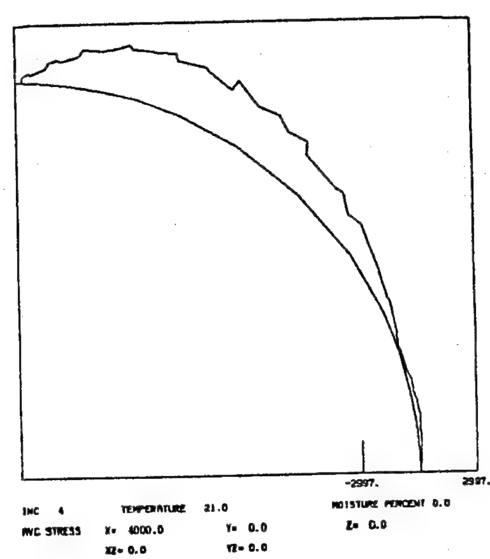
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

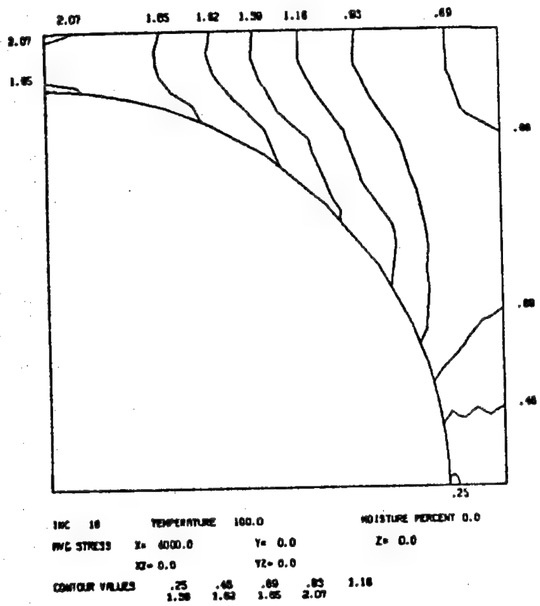


g) Interface Normal Stress (psi)

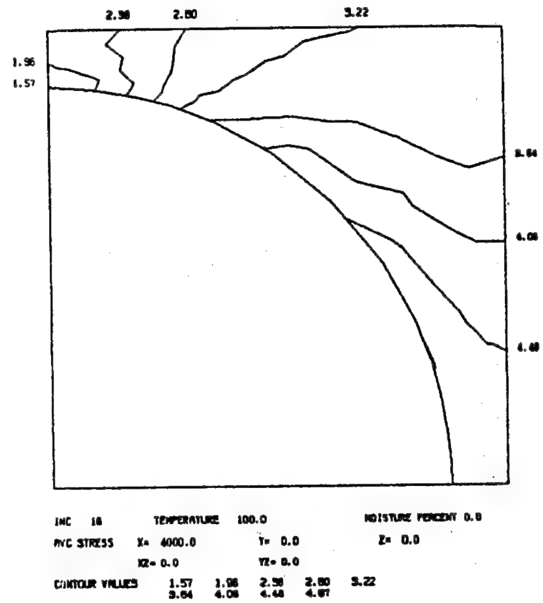


h) Interface Shear Stress (psi)

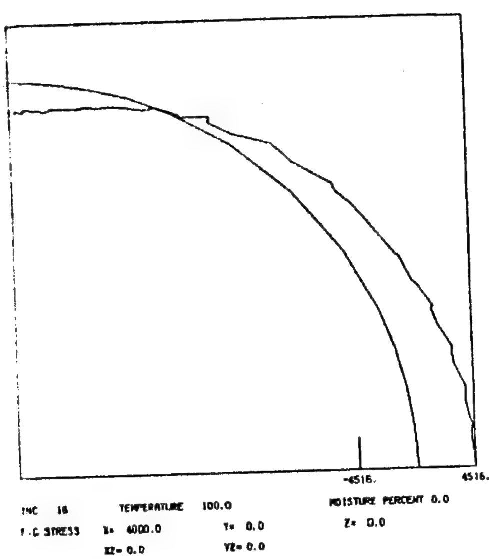
Figure E29 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



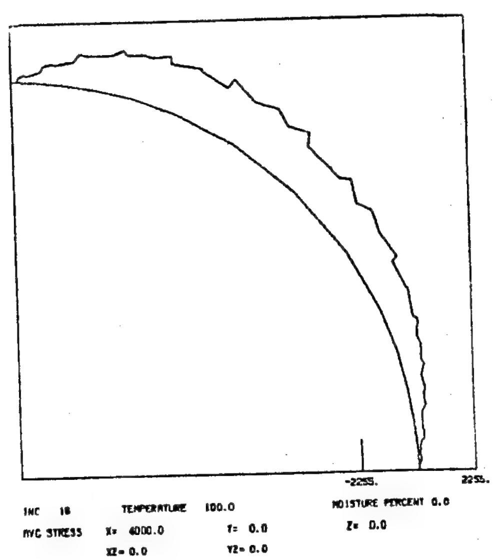
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

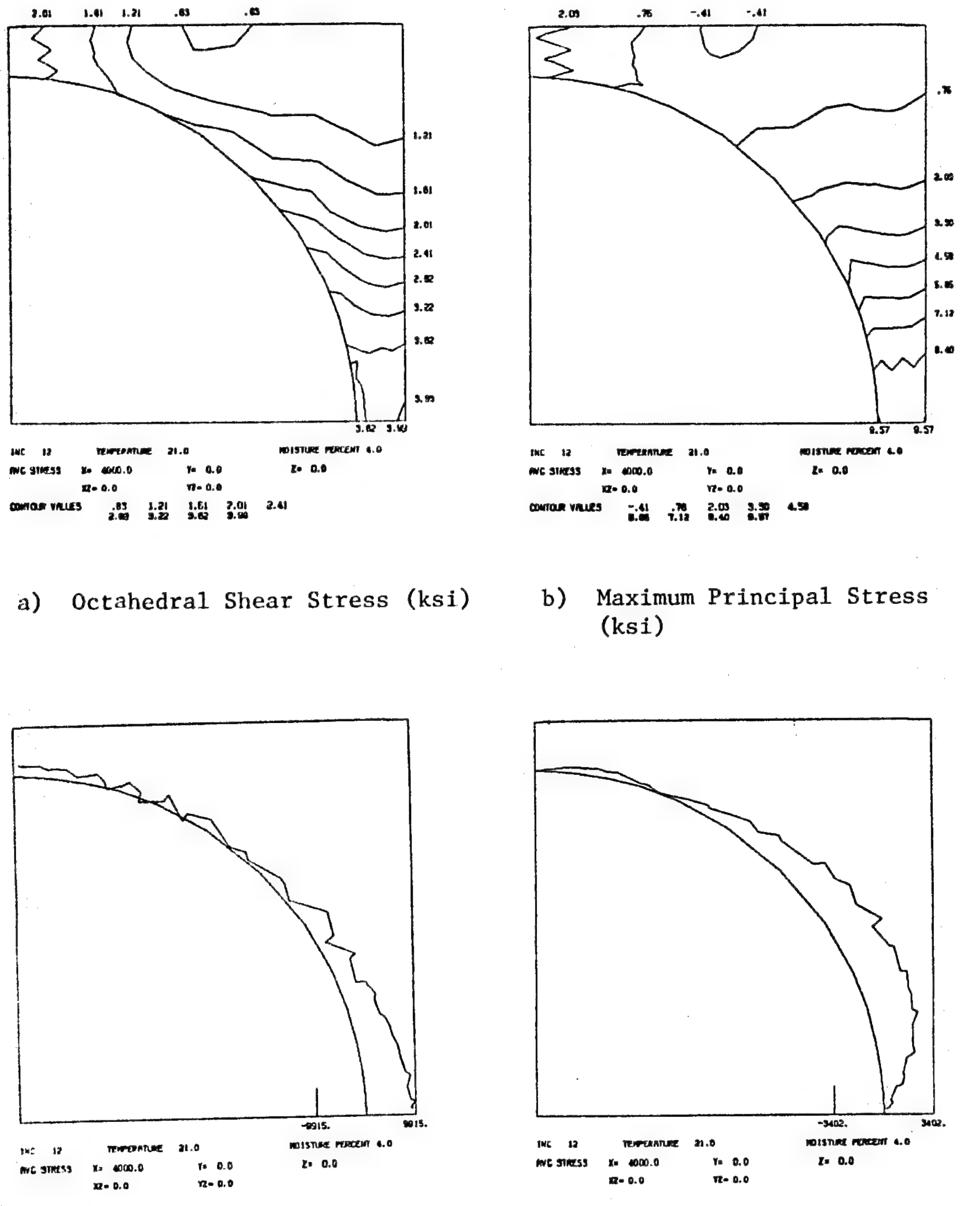


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

Figure E30. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



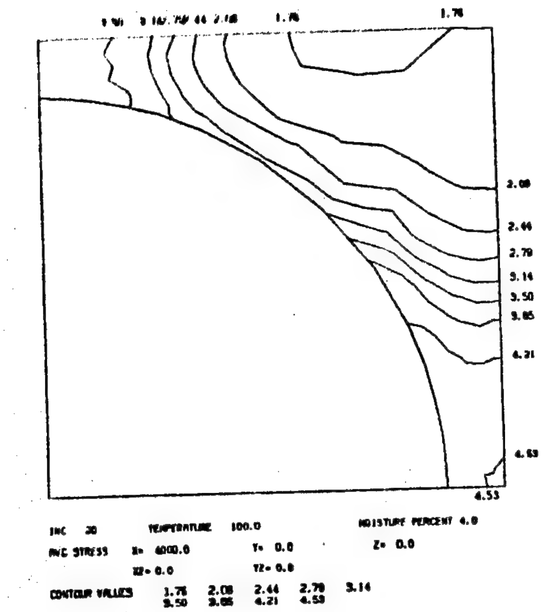
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

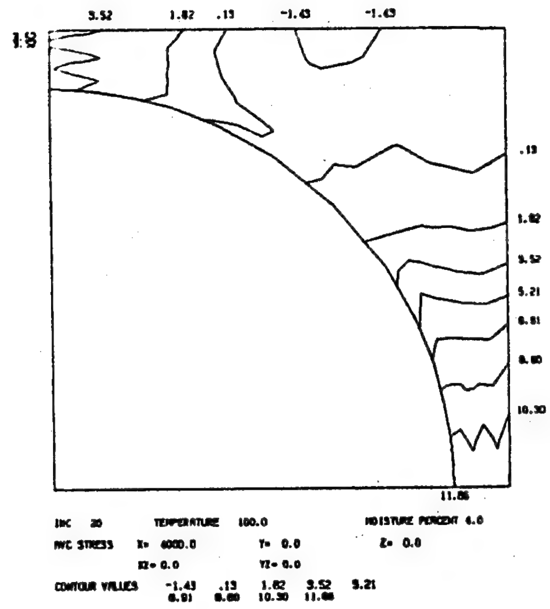
c) Interface Normal Stress (psi)

d) Interface Shear Stress (psi)

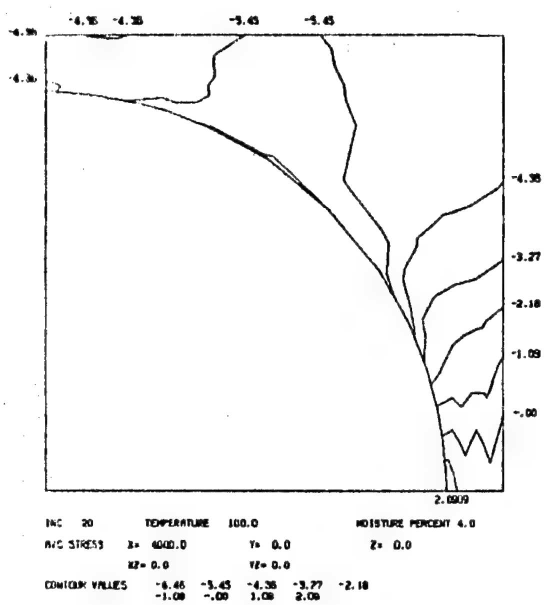
Figure E31. AS4/220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, 4.0 Percent Moisture (RTW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



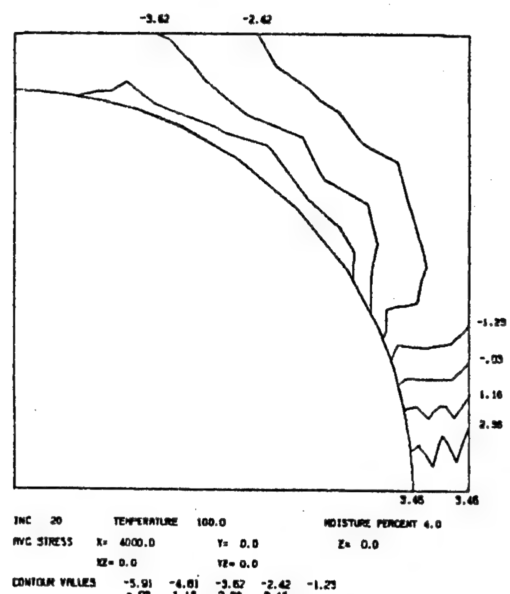
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

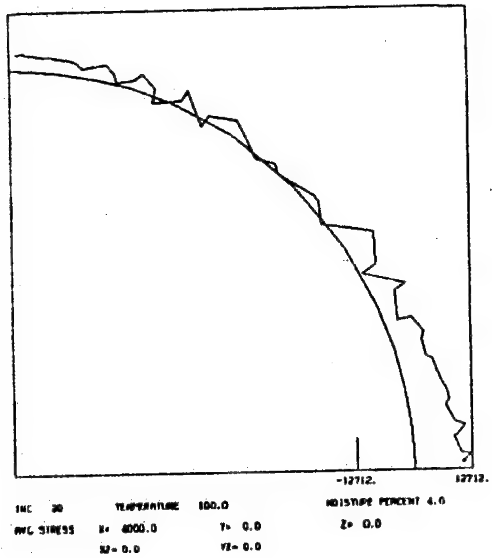


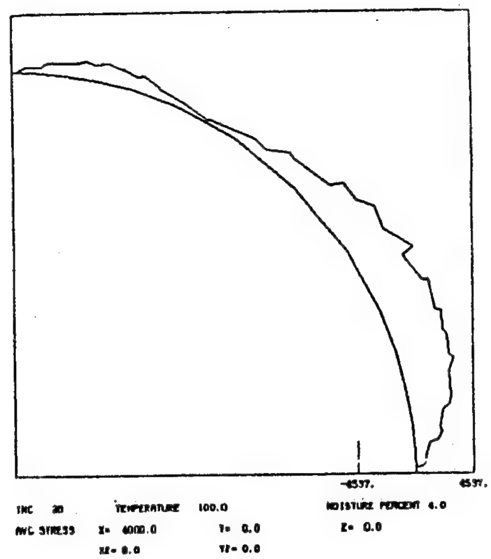
c) Minimum Principal Stress (ksi)



d) Intermediate Principal Stress (ksi)

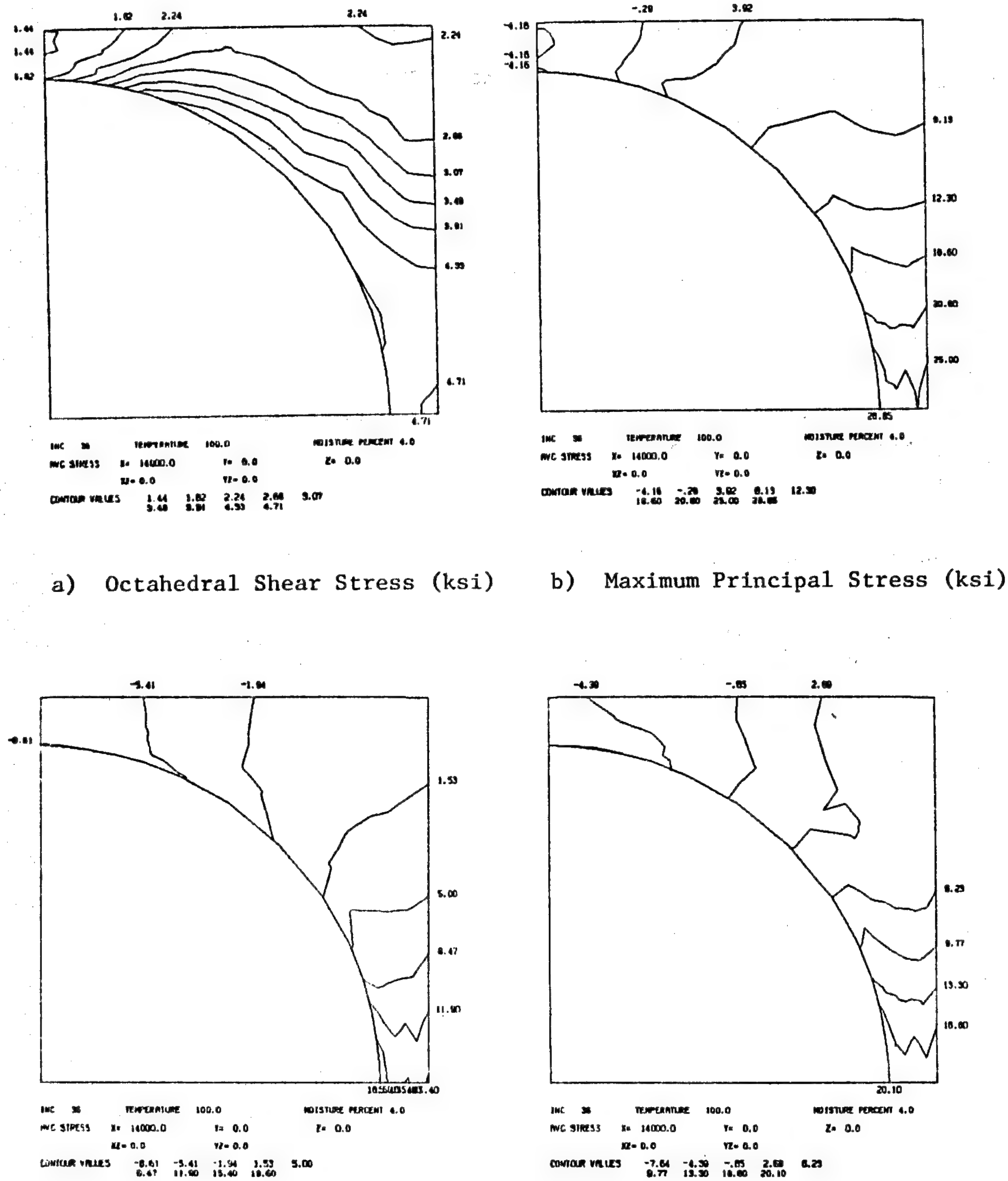
Figure E32. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.





e) Interface Normal Stress (psi) f) Interface Shear Stress (psi)

Figure E32 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



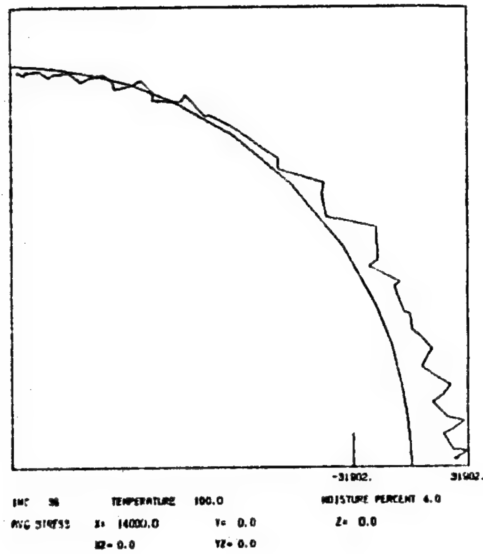
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

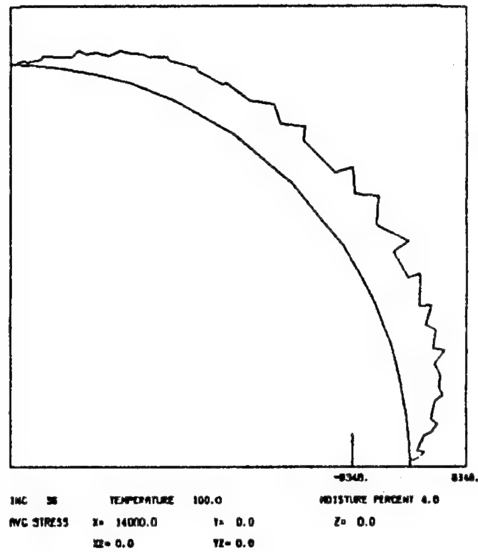
c) Minimum Principal Stress (ksi)

d) Intermediate Principal Stress (ksi)

Figure E33. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.

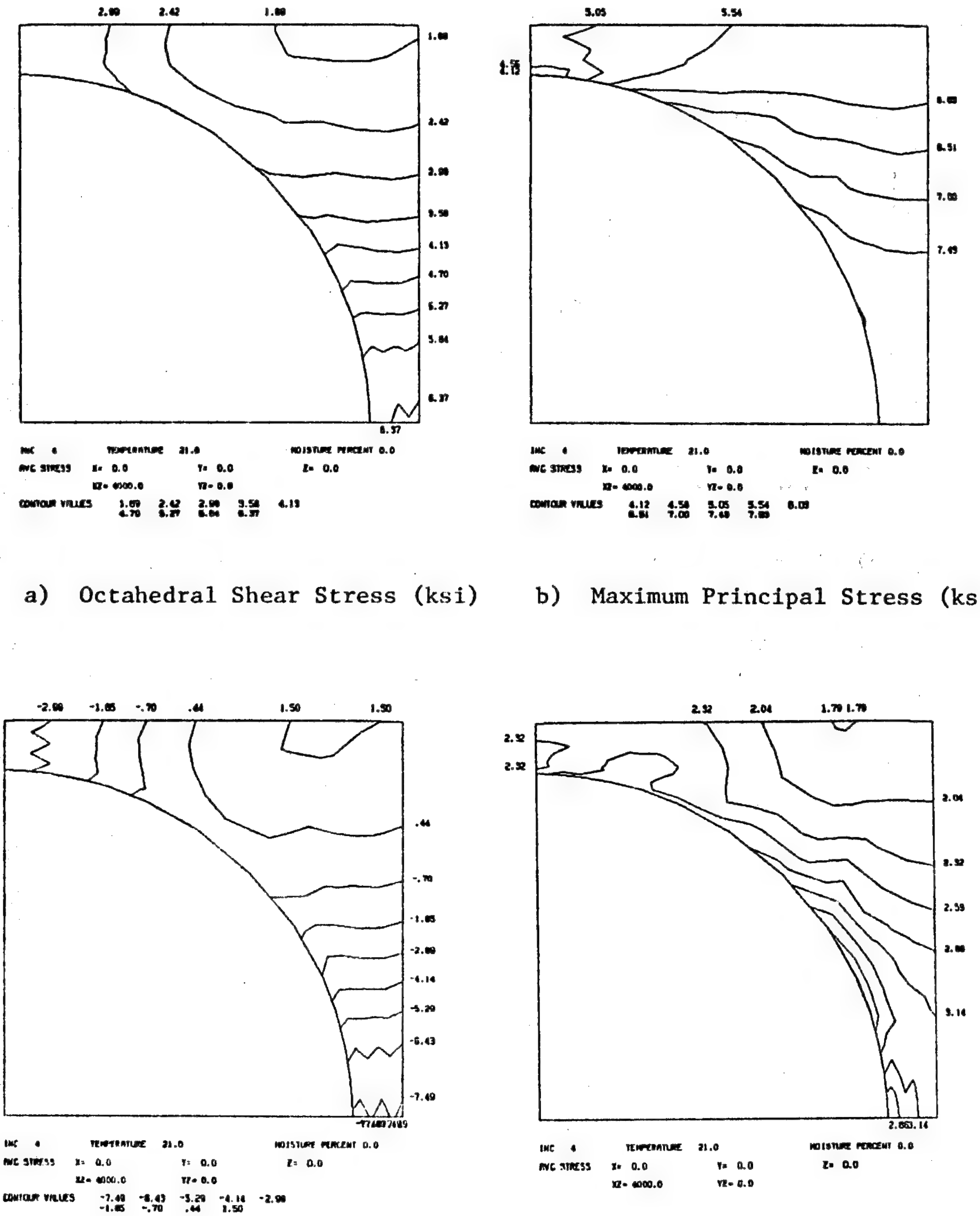


e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

Figure E33 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.



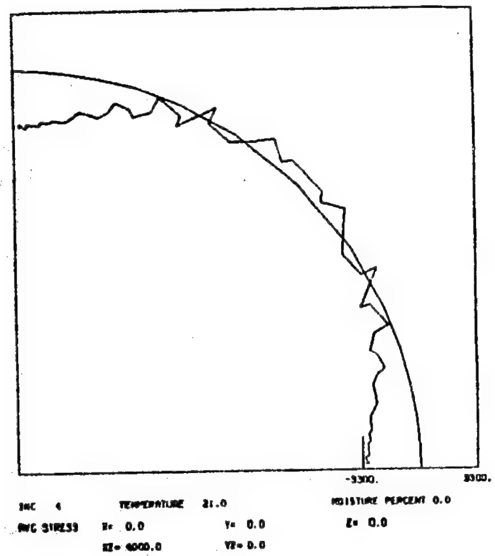
a) Octahedral Shear Stress (ksi)

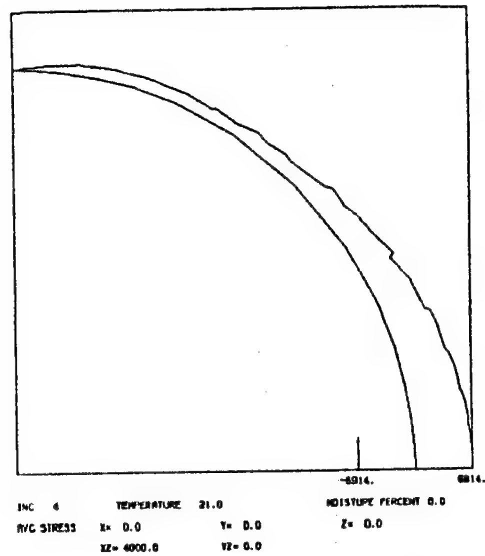
b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi)

d) Intermediate Principal Stress (ksi)

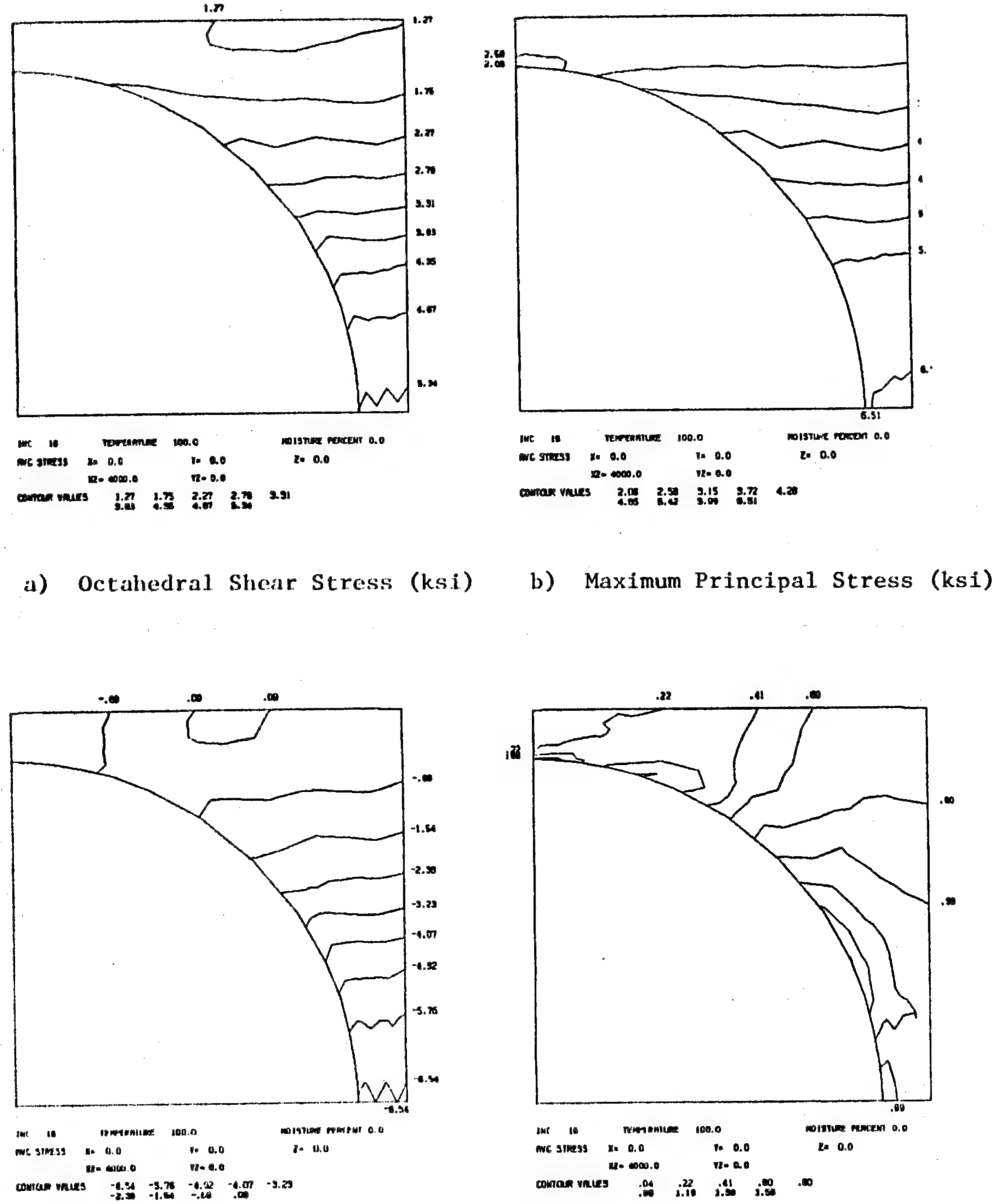
Figure E34. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.





e) Interface Normal Stress (psi)   f) Interface Shear Stress (psi)

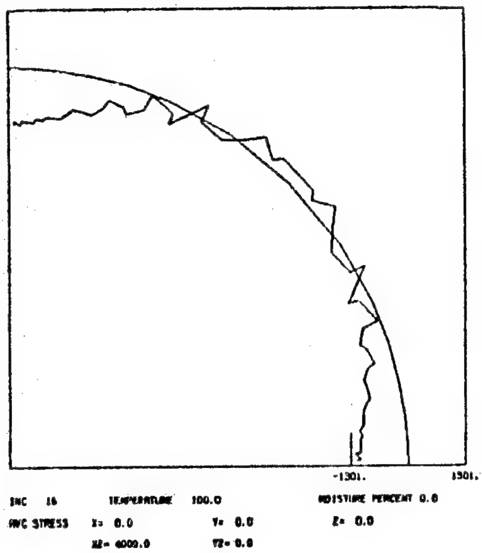
Figure E34 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



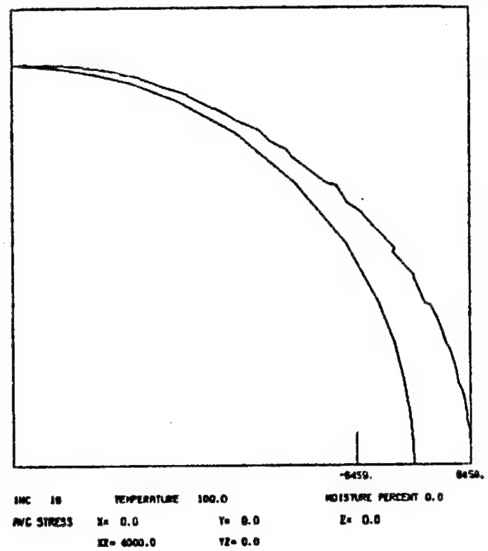
a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi) d) Intermediate Principal Stress (ksi)

Figure E35. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100 C,Dry (ETD);27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

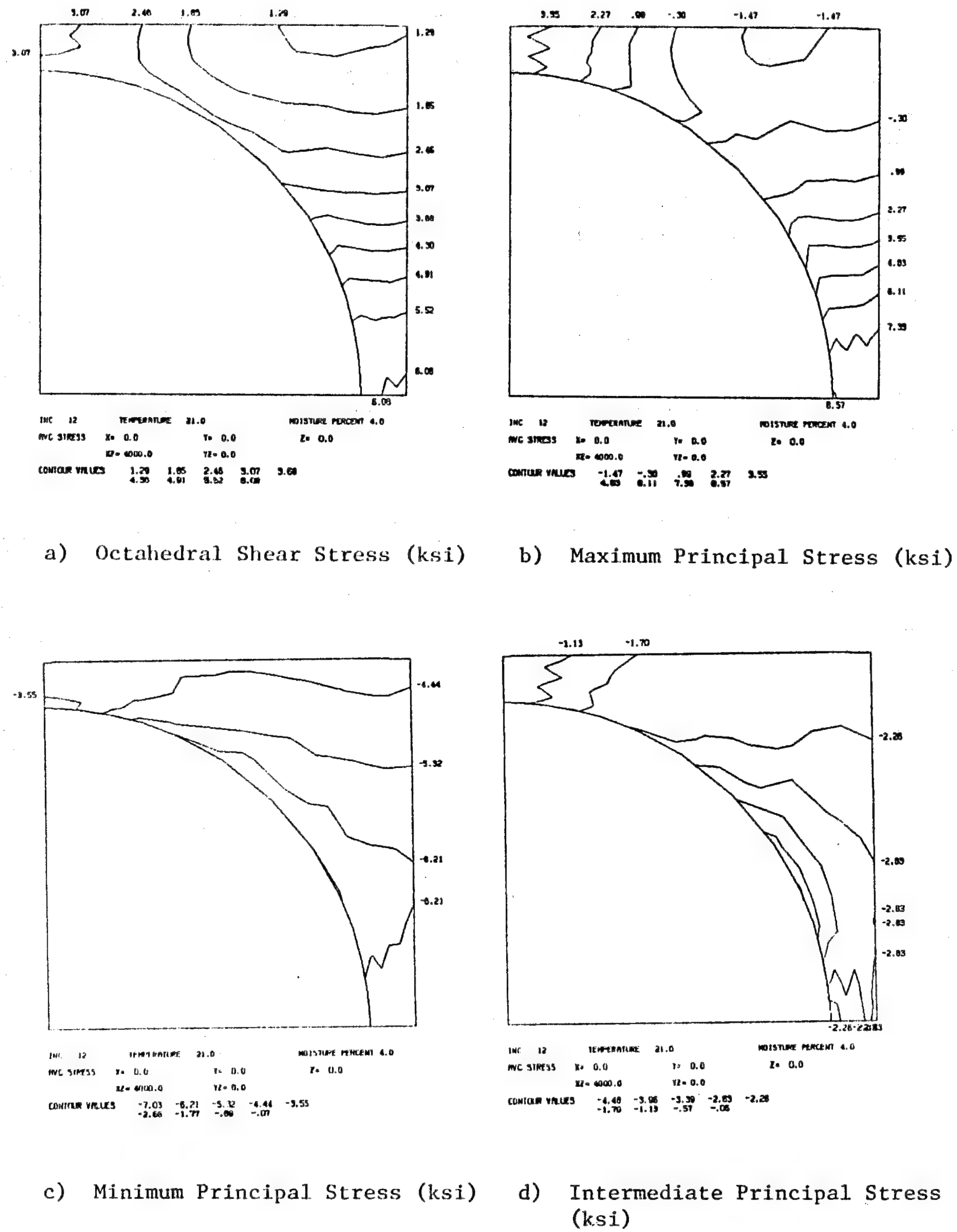


e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

Figure E35 (continued). AS4-2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



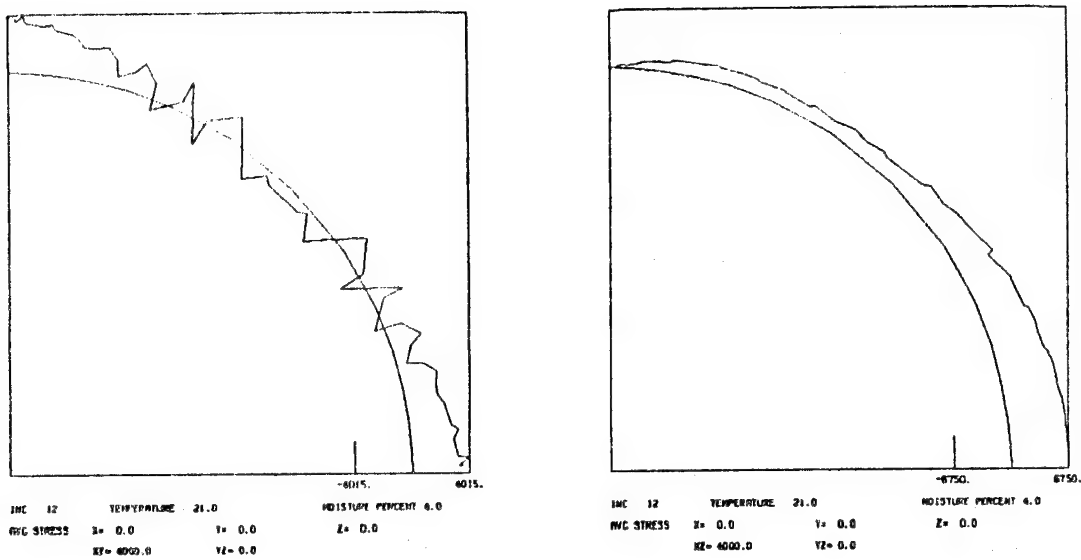
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi)

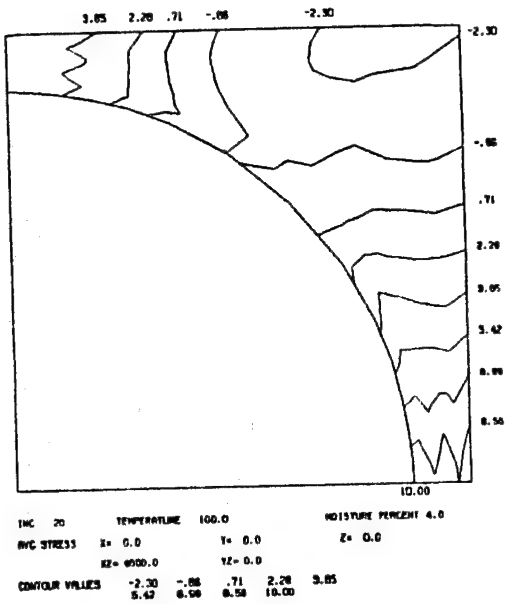
d) Intermediate Principal Stress (ksi)

Figure E36. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 21°C, 4.0 Percent Moisture (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

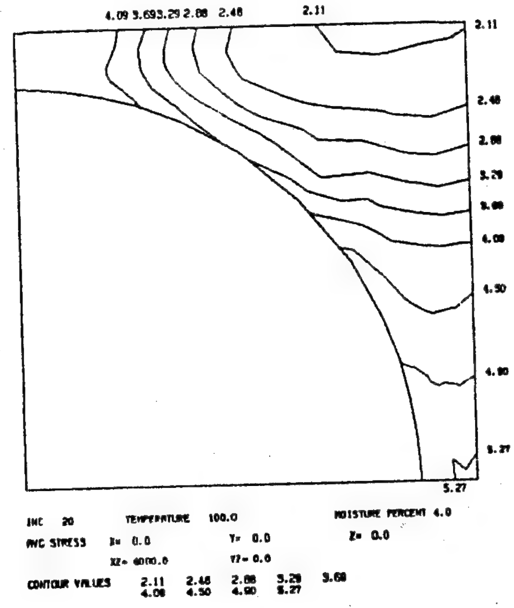


e) Interface Normal Stress (psi) f) Interface Shear Stress (psi)

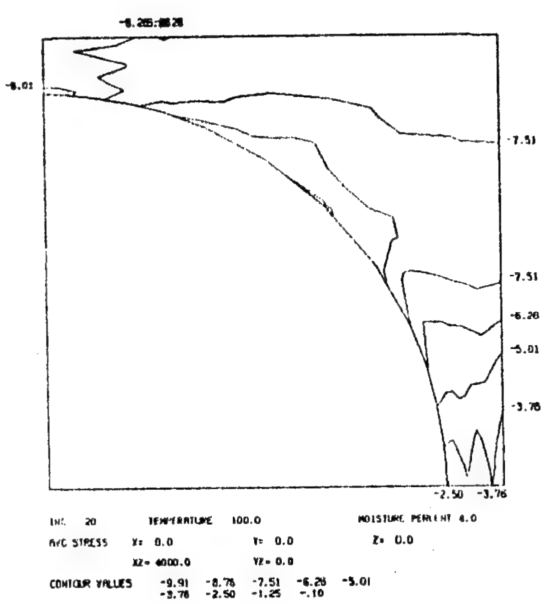
Figure E36 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 21°C, 4.0 Percent Moisture (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



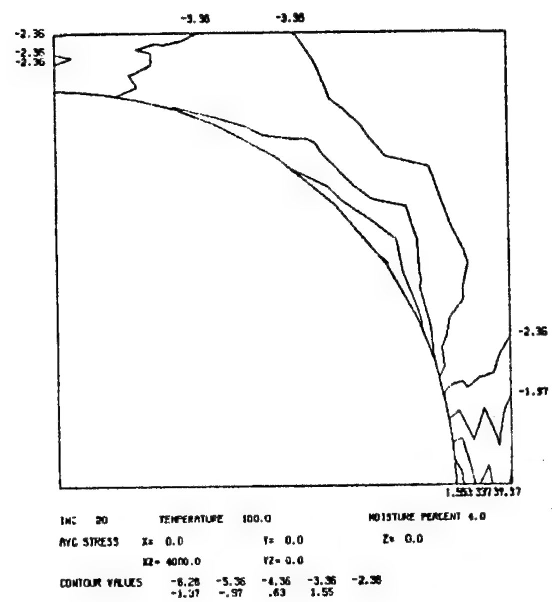
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

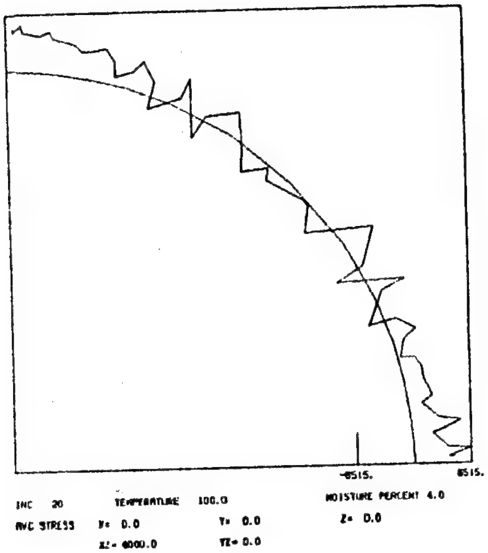


c) Minimum Principal Stress (ksi)

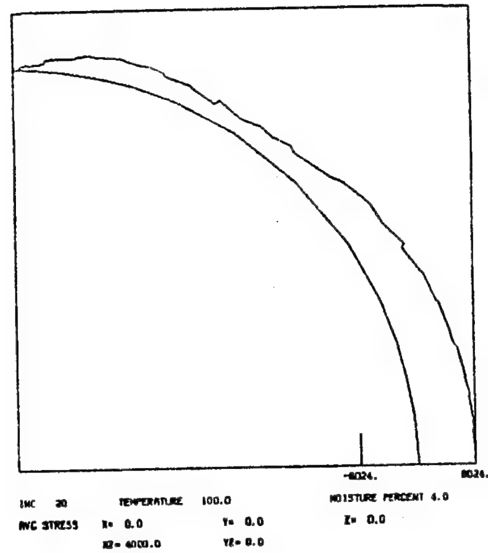


d) Intermediate Principal Stress (ksi)

Figure E37. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

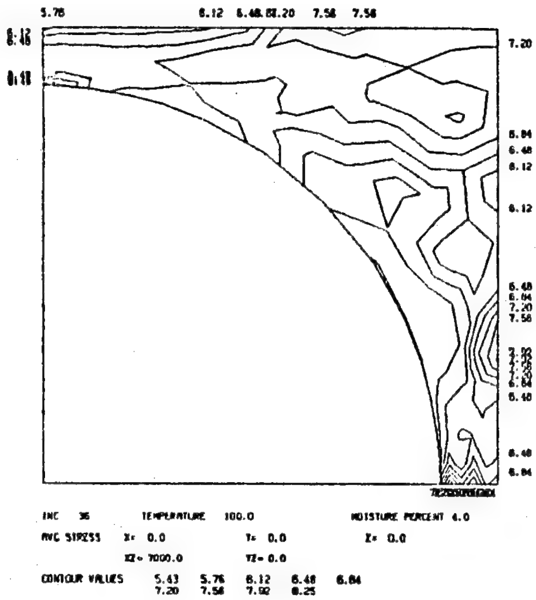


e) Interface Normal Stress (psi)

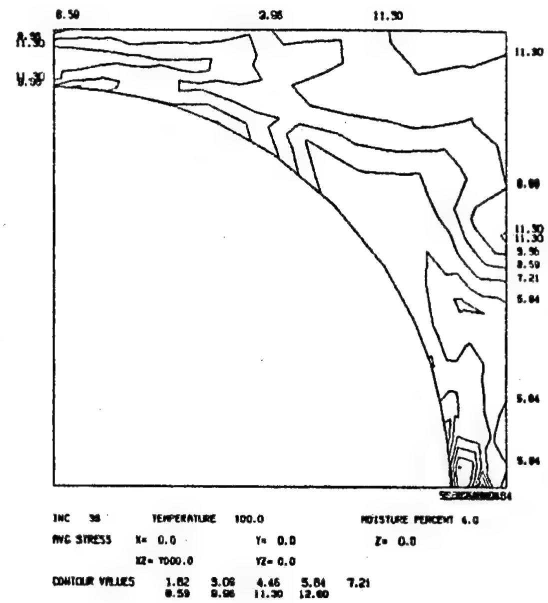


f) Interface Shear Stress (psi)

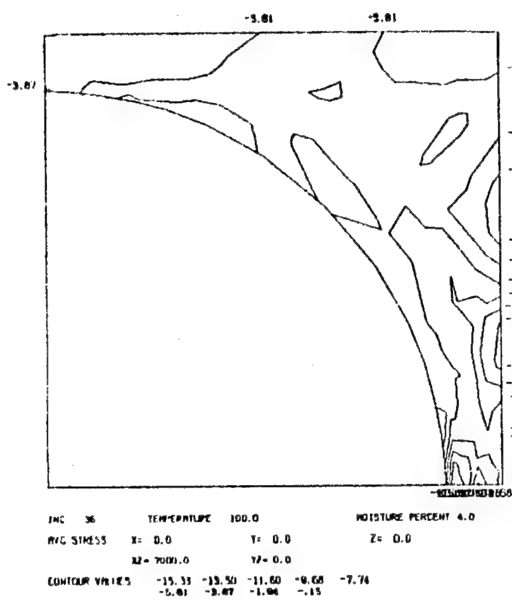
Figure E37 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



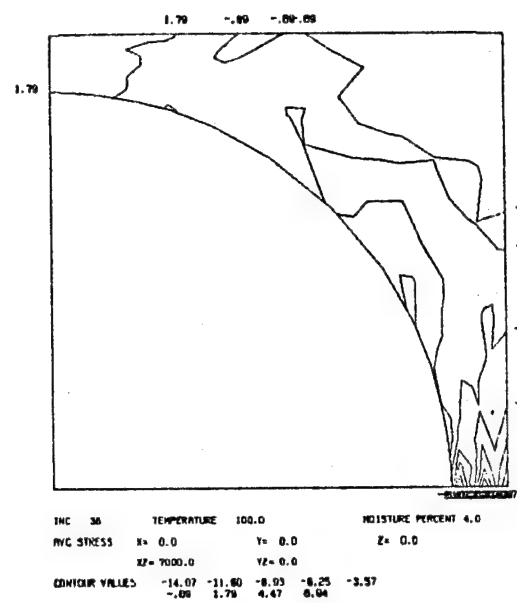
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

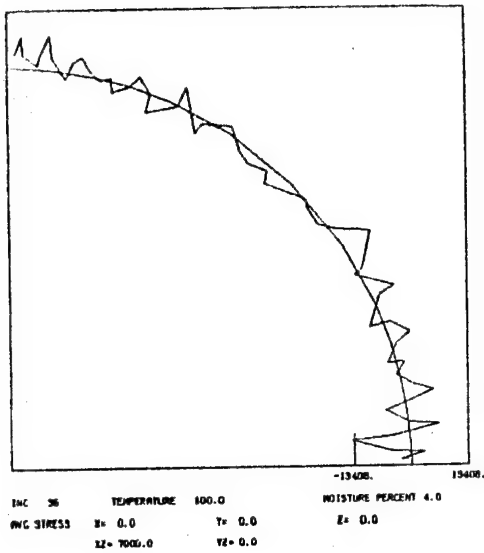


c) Minimum Principal Stress (ksi)

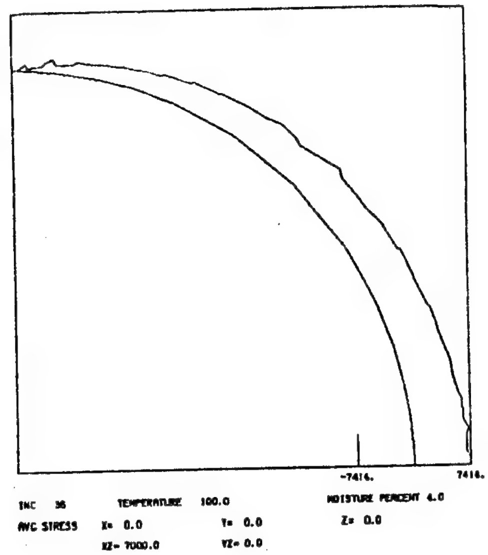


d) Intermediate Principal Stress (ksi)

Figure E38. AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.



e) Interface Normal Stress (psi)

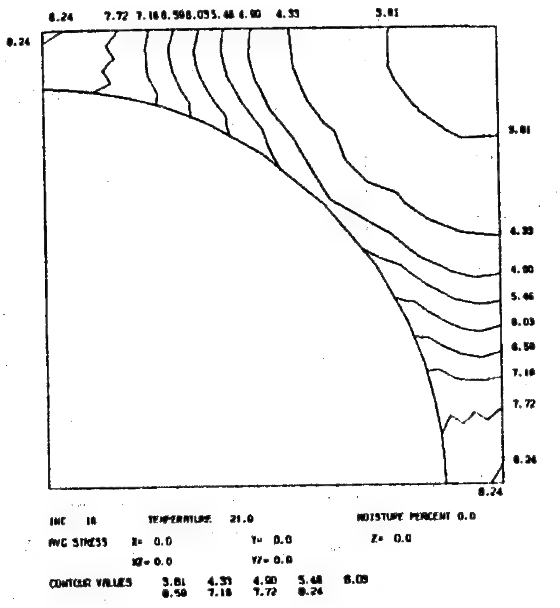


f) Interface Shear Stress (psi)

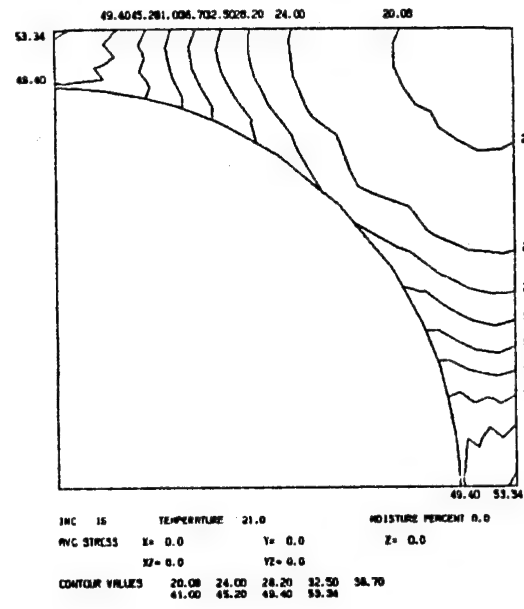
Figure E38 (continued). AS4/2220-3 Graphite/Epoxy Unidirectional Composite, 100°C, 4.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.

APPENDIX E3

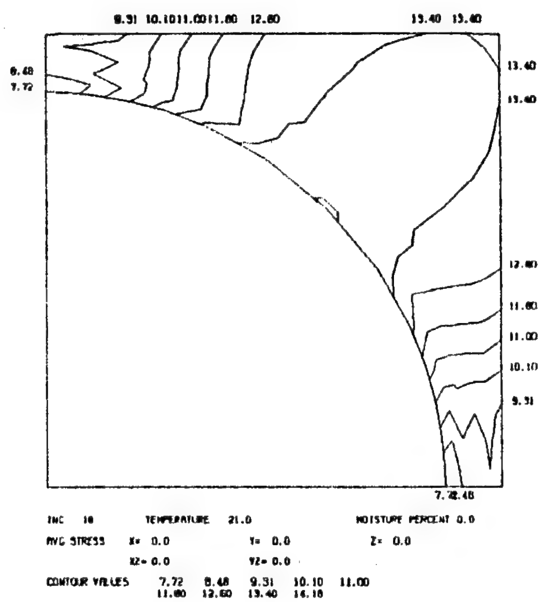
AS4/914 GRAPHITE/EPOXY UNIDIRECTIONAL COMPOSITE



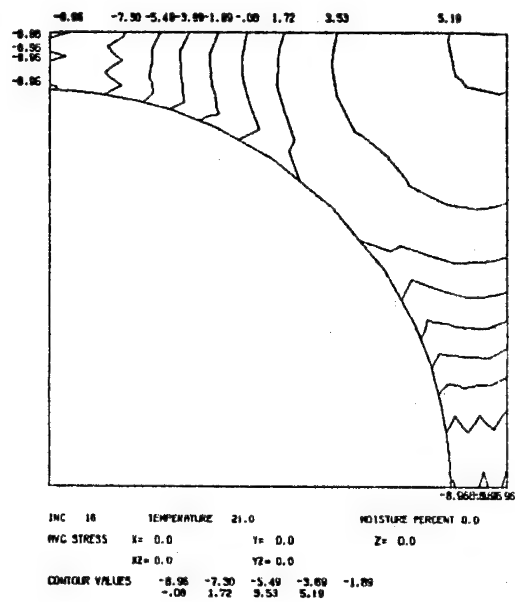
a) Octahedral Shear Stress (ksi)



b) Octahedral Shear Strain (10^{-3})

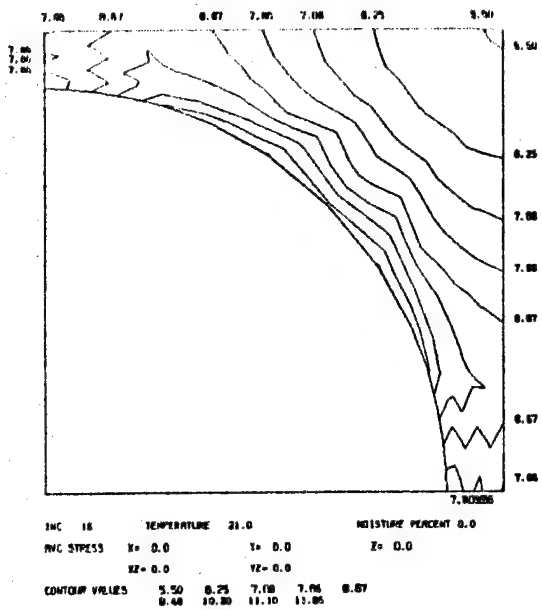


c) Maximum Principal Stress (ksi)

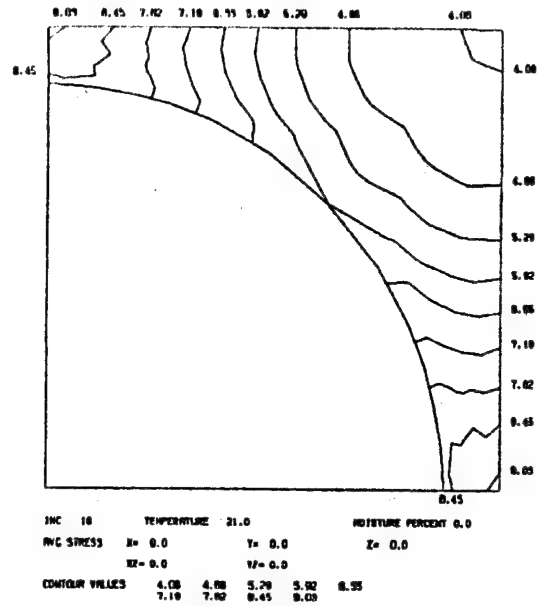


d) Minimum Principal Stress (ksi)

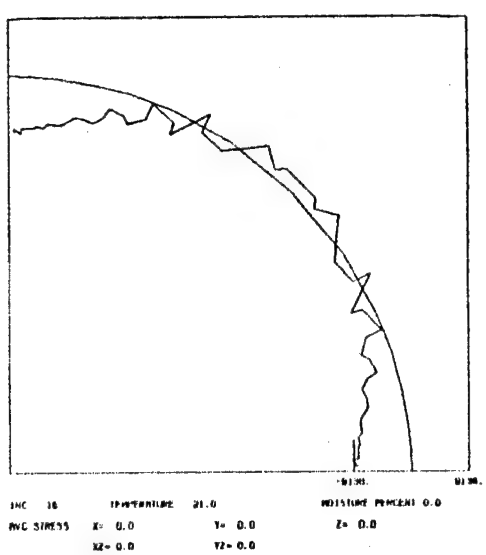
Figure E39. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



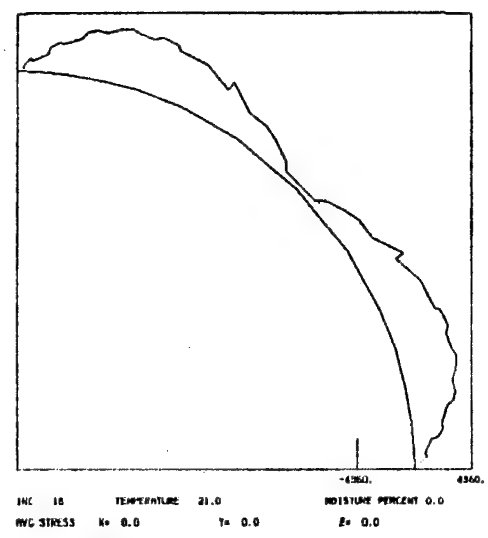
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

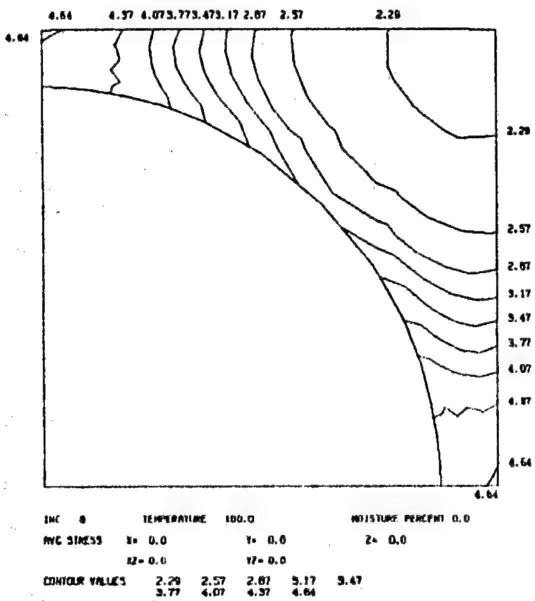


g) Interface Normal Stress (psi)

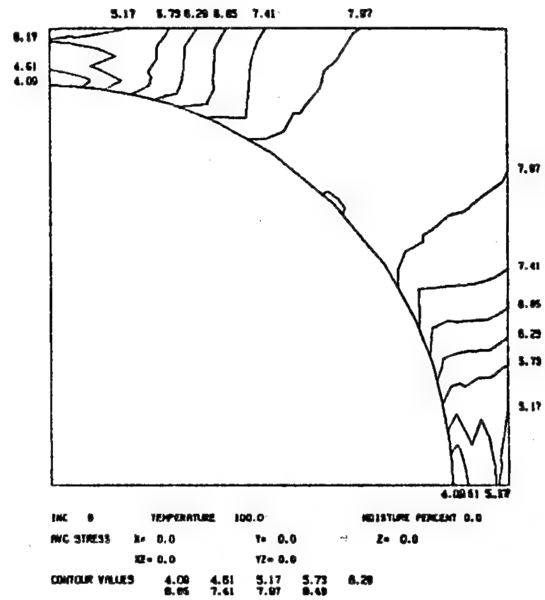


h) Interfacial Shear Stress (psi)

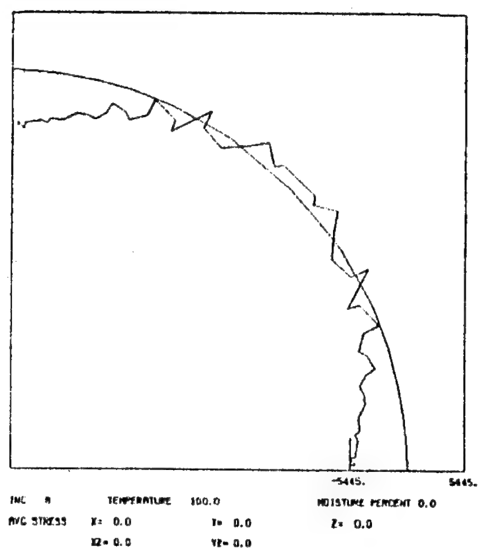
Figure E39 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); No Mechanical Loading.



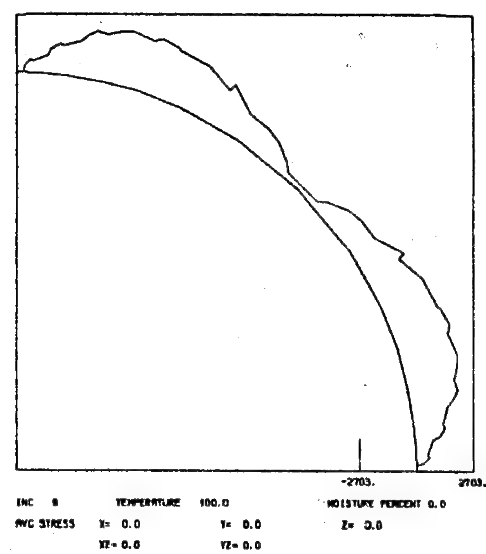
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

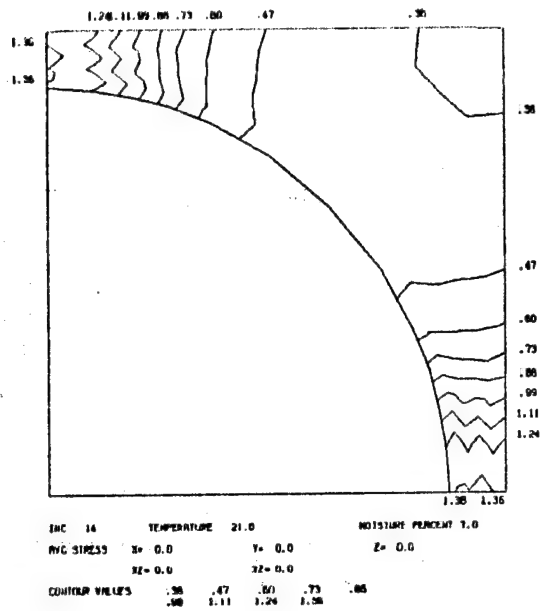


c) Interface Normal Stress (psi)

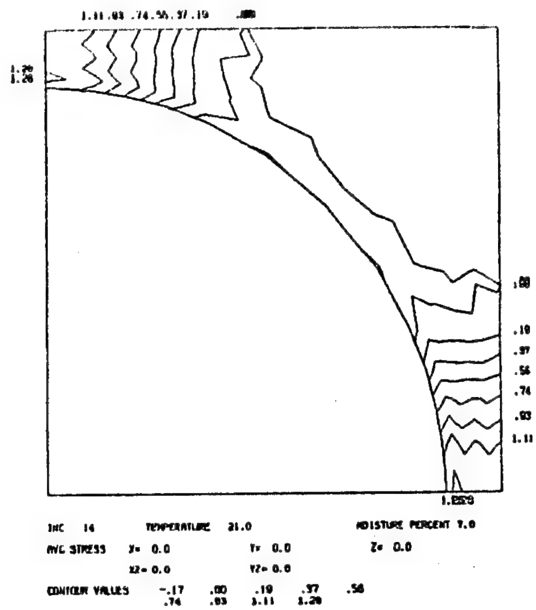


d) Interface Shear Stress (psi)

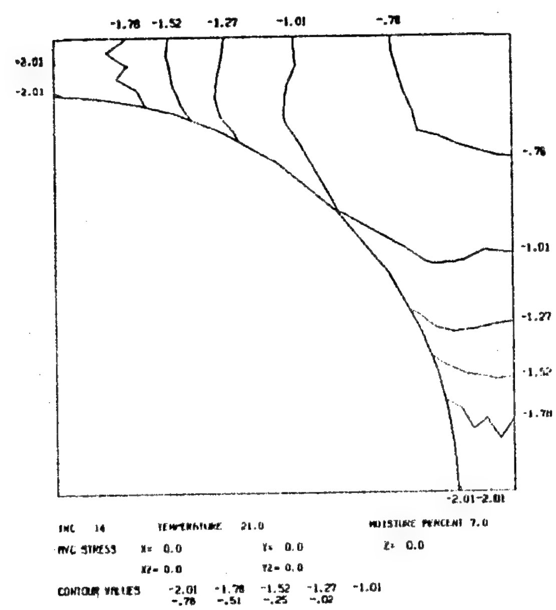
Figure E40. AS4/914 Graphite/Epoxy Unidirectional Composite, $100^{\circ}C$, Dry (ETD); No Mechanical Loading.



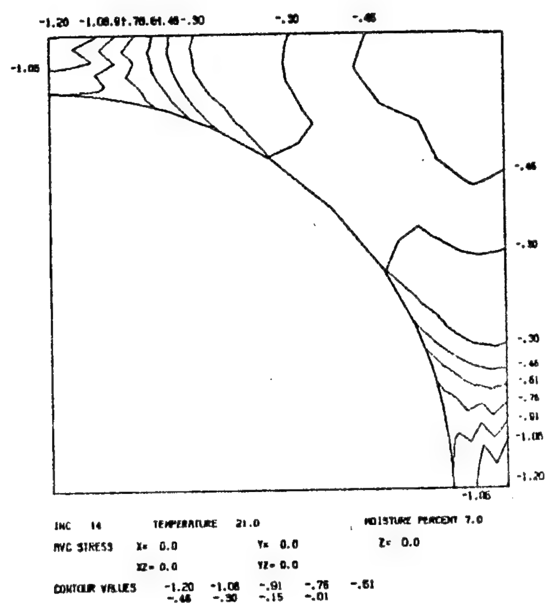
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

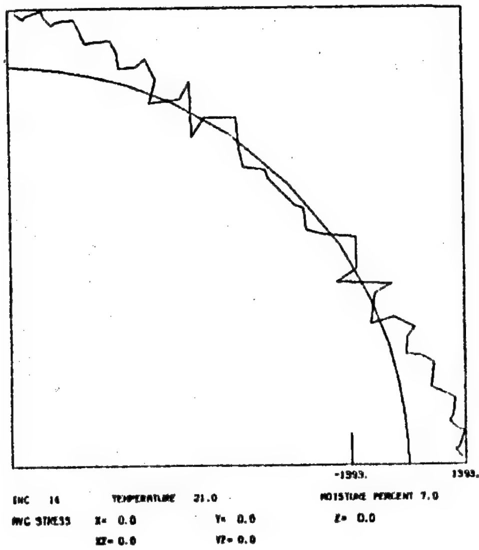


c) Maximum Principal Stress (ksi)

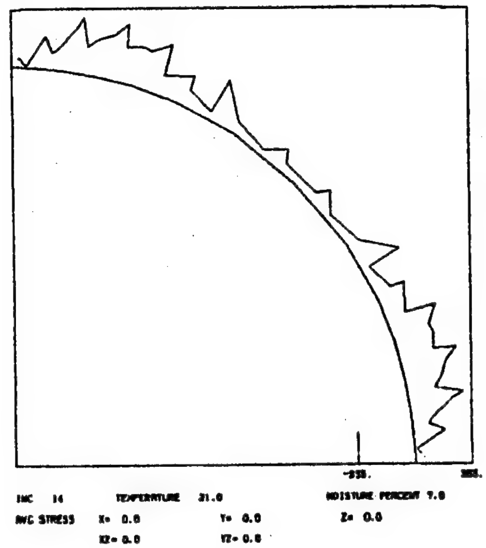


d) Intermediate Principal Stress (ksi)

Figure E41. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, 7.0 Percent Moisture (RTW); No Mechanical Loading.

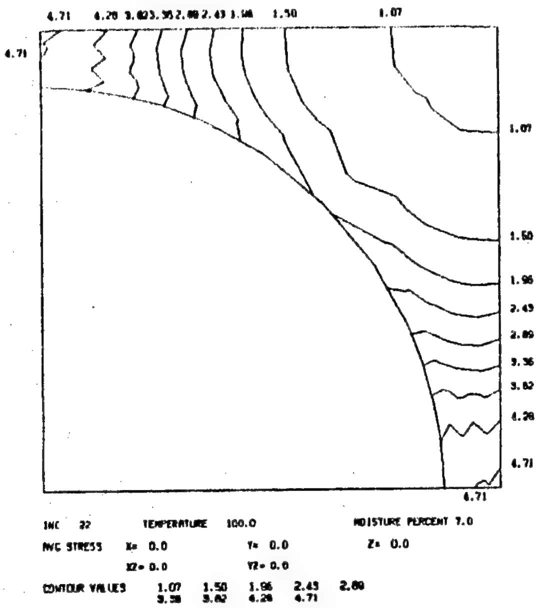


e) Interface Normal Stress (psi)

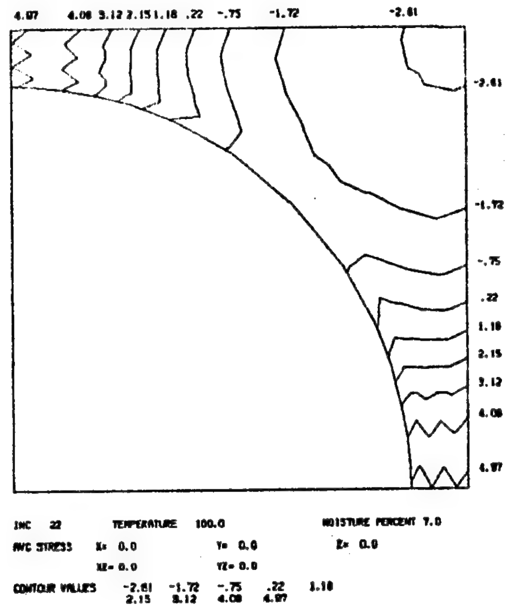


f) Interface Shear Stress (psi)

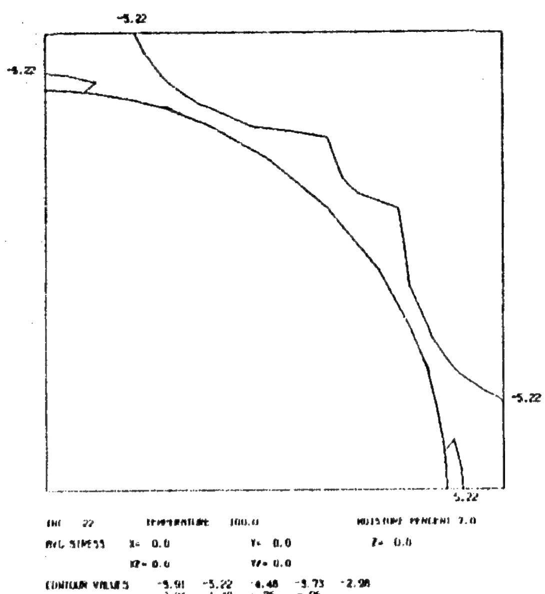
Figure E41 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, 7.0 Percent Mositure (RTW); No Mechanical Loading.



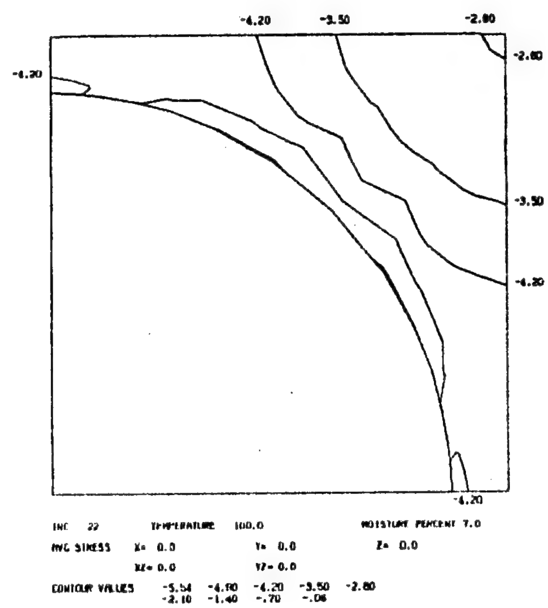
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

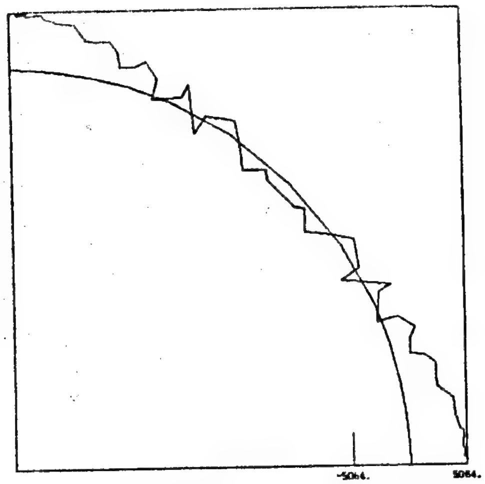


c) Minimum Principal Stress (ksi)

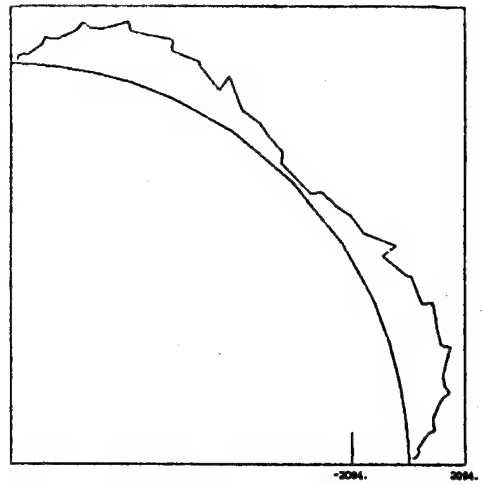


d) Intermediate Principal Stress (ksi)

Figure E42. AS4/914 Graphite/Epoxy Unidirectional Composite, $100^{\circ}C$, 7.0 Percent Moisture (ETW); No Mechanical Loading.

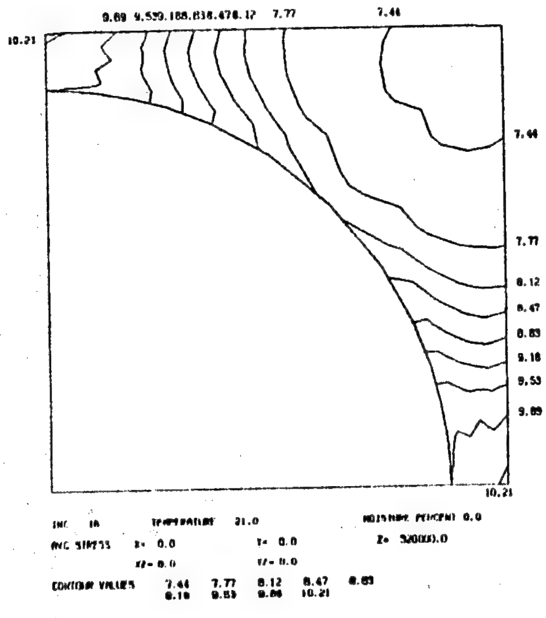


e) Interface Normal Stress (psi)

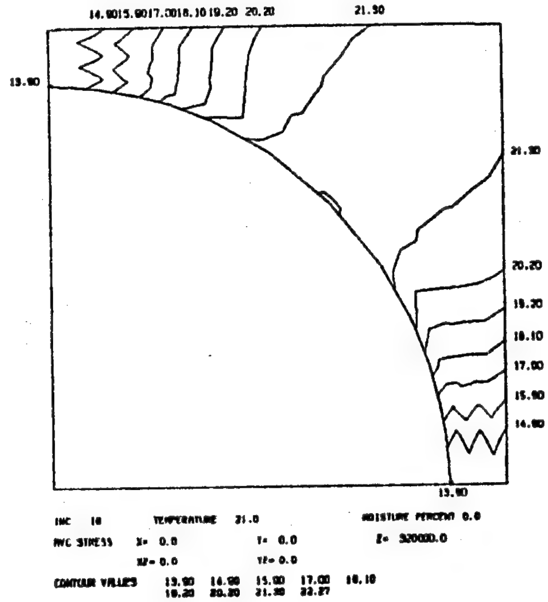


f) Interface Shear Stress (psi)

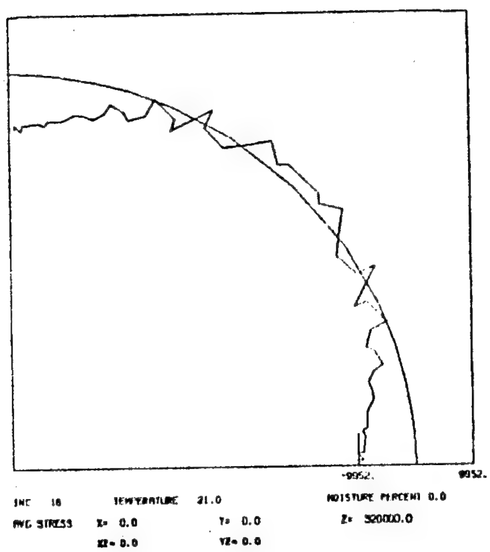
Figure E42 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); No Mechanical Loading.



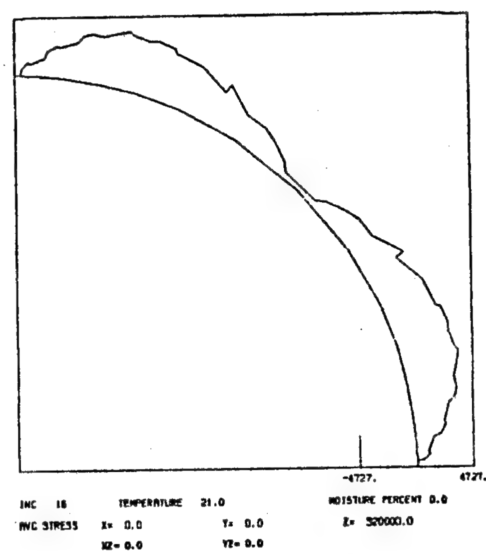
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

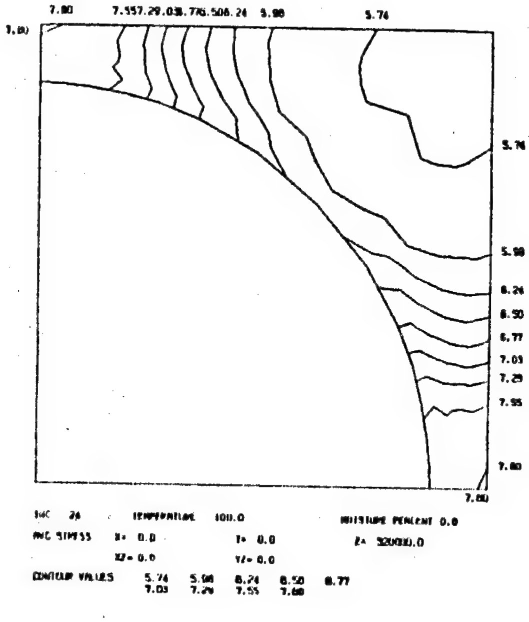


c) Interface Normal Stress (psi)

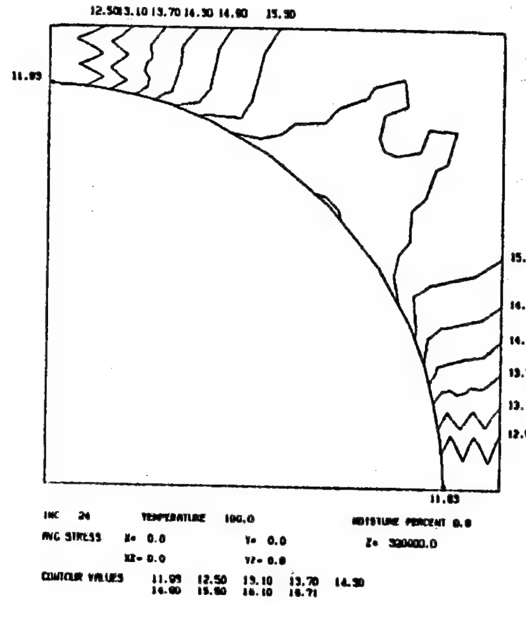


d) Interface Shear Stress (psi)

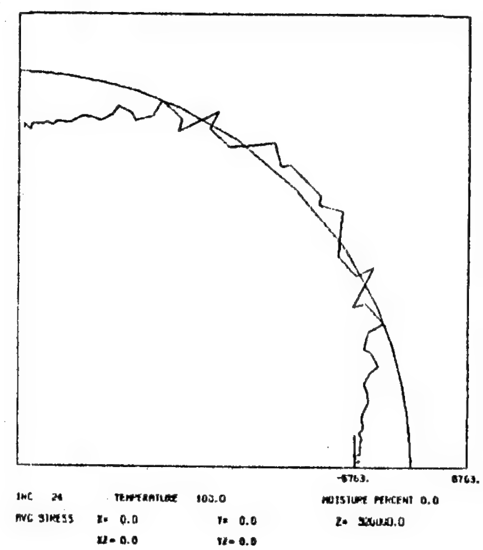
Figure E43. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



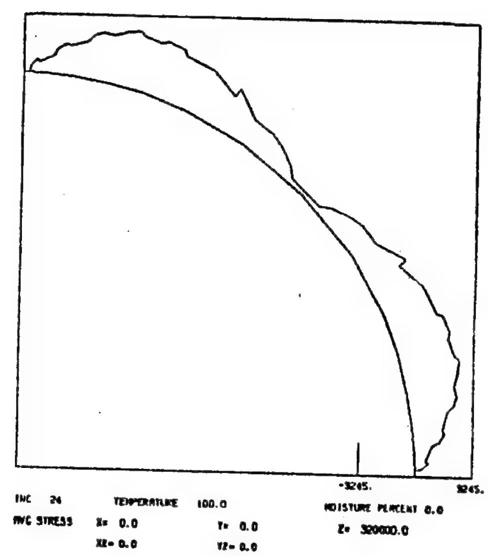
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

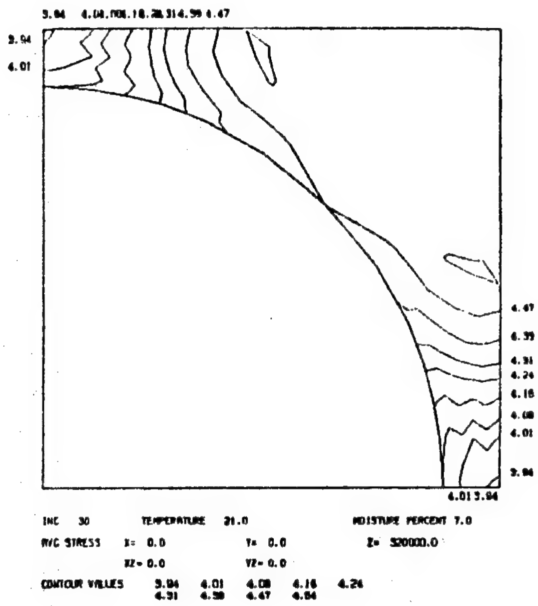


c) Interface Normal Stress (psi)

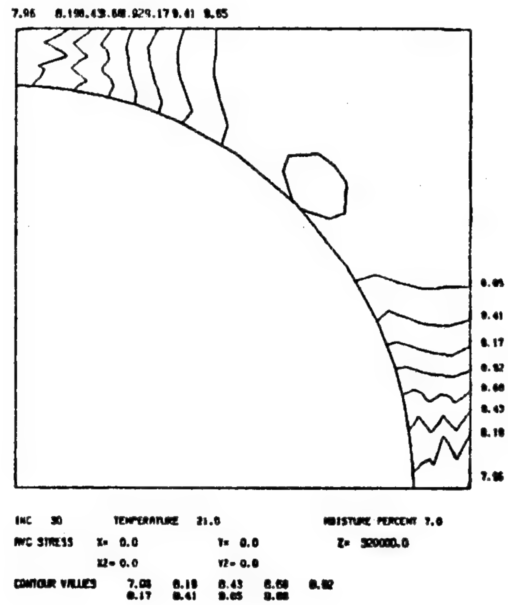


d) Interface Shear Stress (psi)

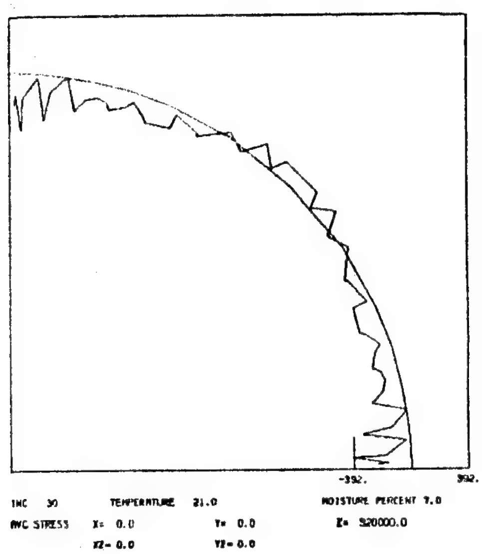
Figure E44. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



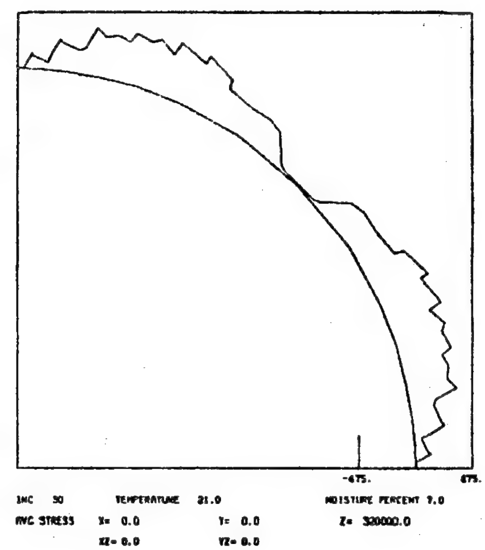
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

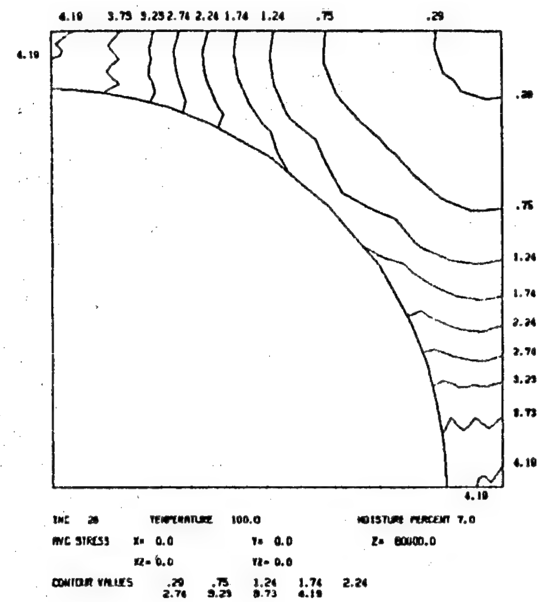


c) Interface Normal Stress (psi)

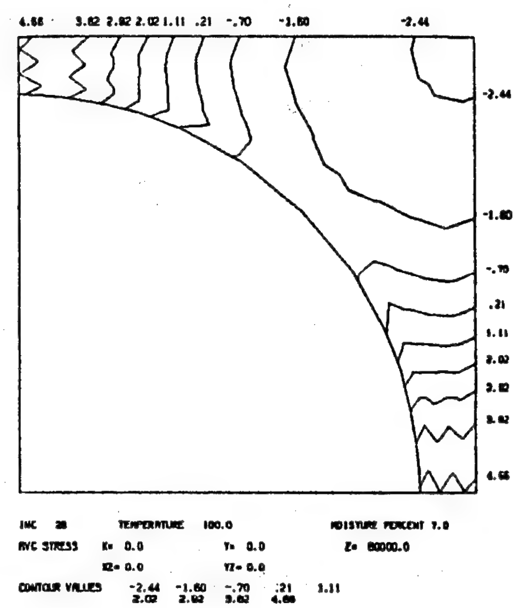


d) Interface Shear Stress (psi)

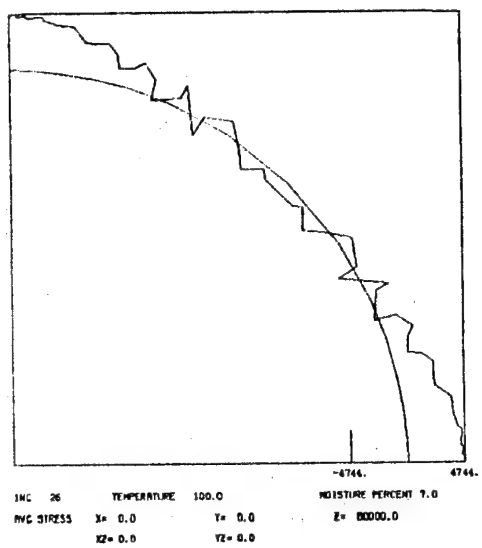
Figure E45. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, 7.0 Percent Moisture (RTW); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



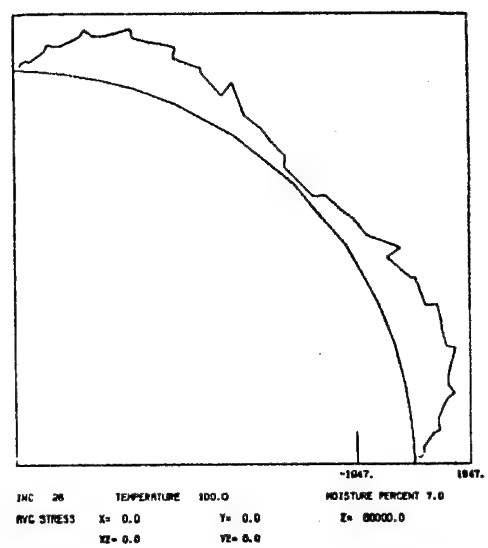
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

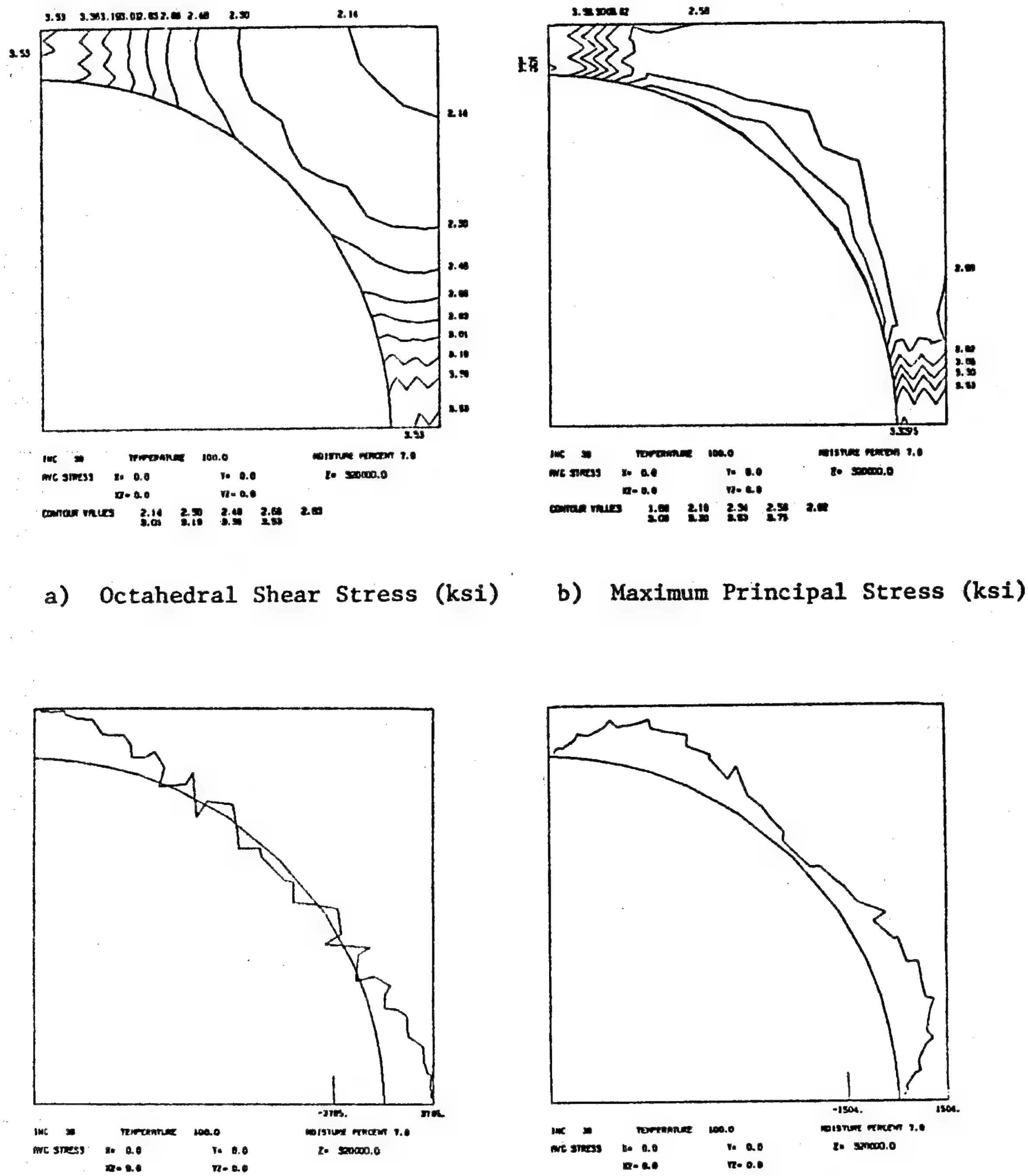


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

Figure E46. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 0.55 GPa (80 ksi) Longitudinal Tensile Applied Stress.



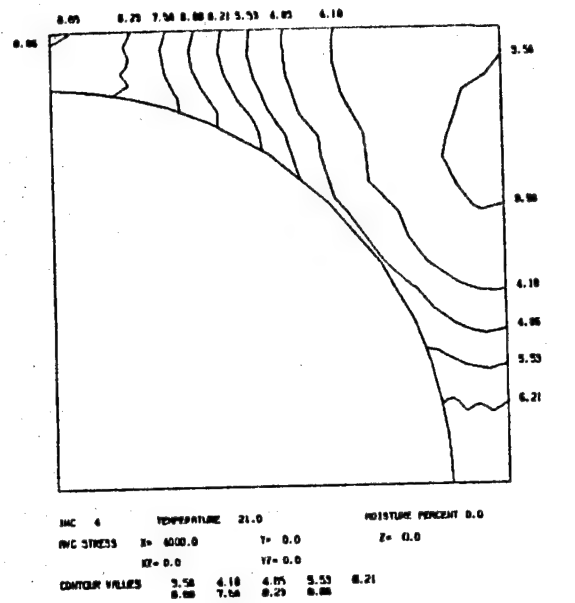
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

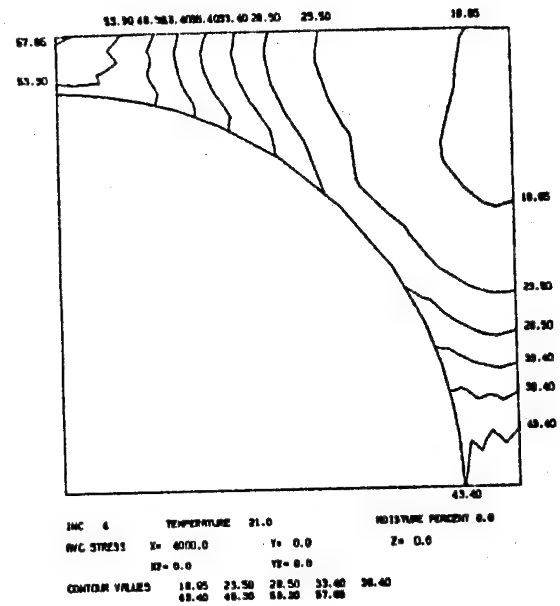
c) Interface Normal Stress (psi)

d) Interface Shear Stress (psi)

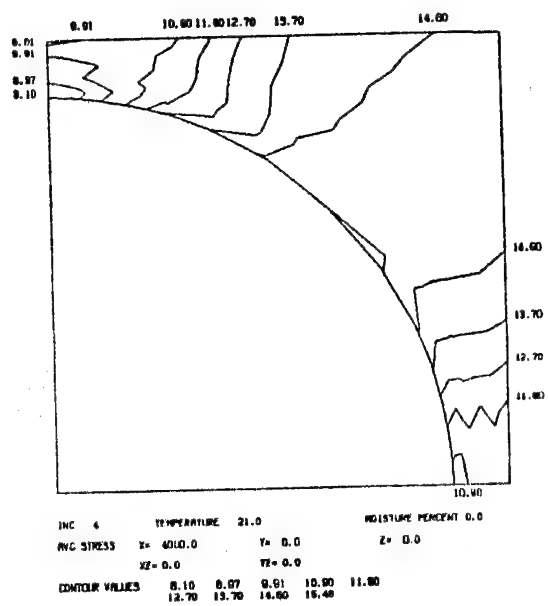
Figure E47. AS4/914 Graphite/Epoxy Unidirectional Composite, $100^{o}C$ 7.0 Percent Moisture (ETW); 2.20 GPa (320 ksi) Longitudinal Tensile Applied Stress.



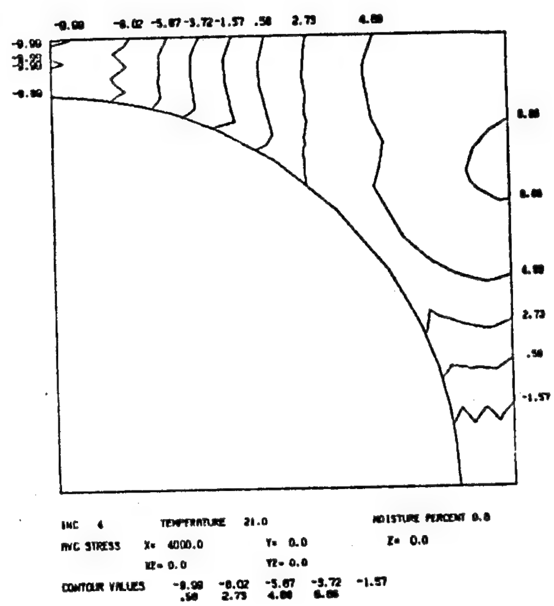
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

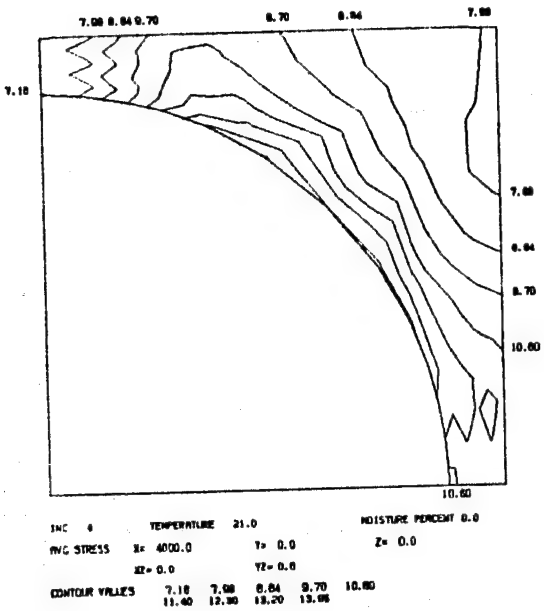


c) Minimum Principal Stress (ksi)

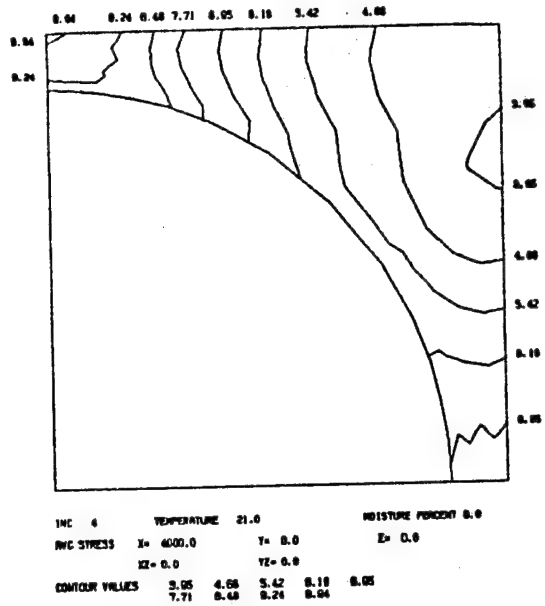


d) Intermediate Principal Stress (ksi)

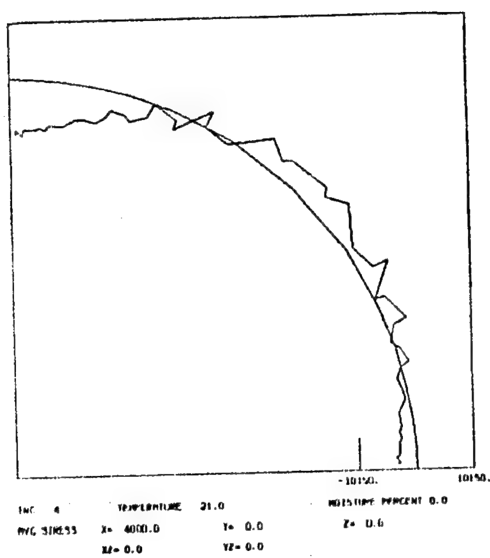
Figure E48. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



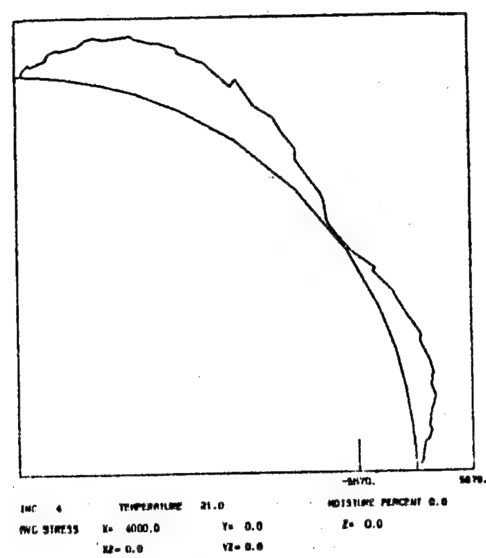
e) Intermediate Principal Stress (ksi)



f) Maximum Shear Stress (ksi)

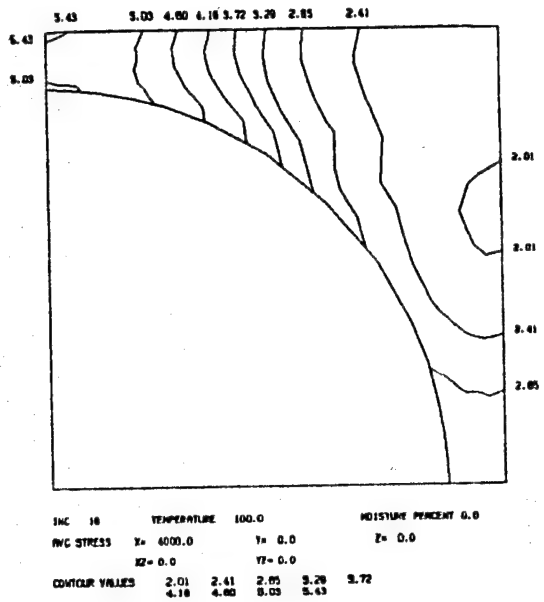


g) Interface Normal Stress (psi)

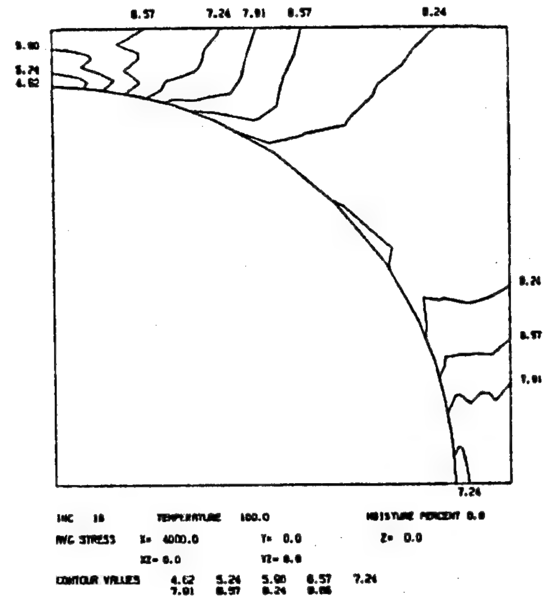


h) Interface Shear Stress (psi)

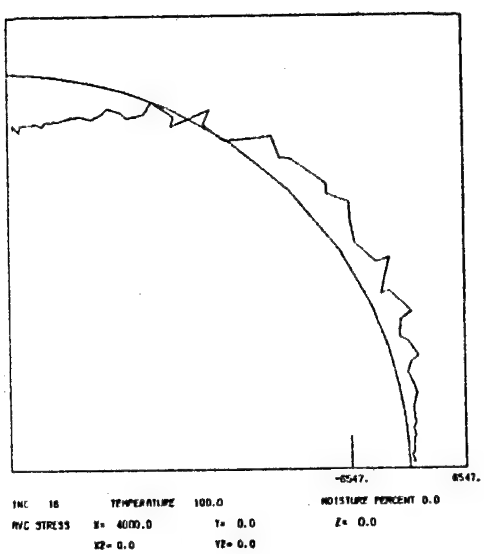
Figure E48 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



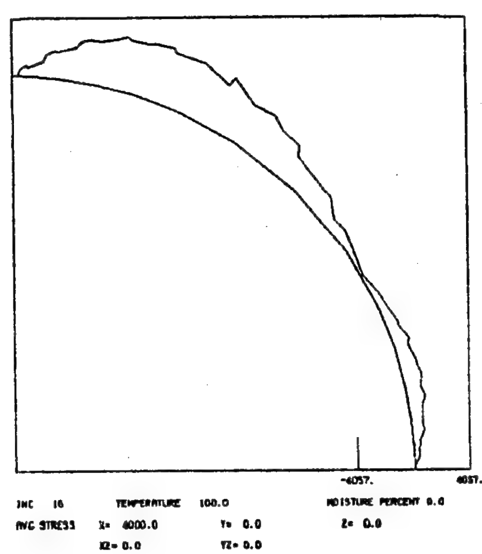
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

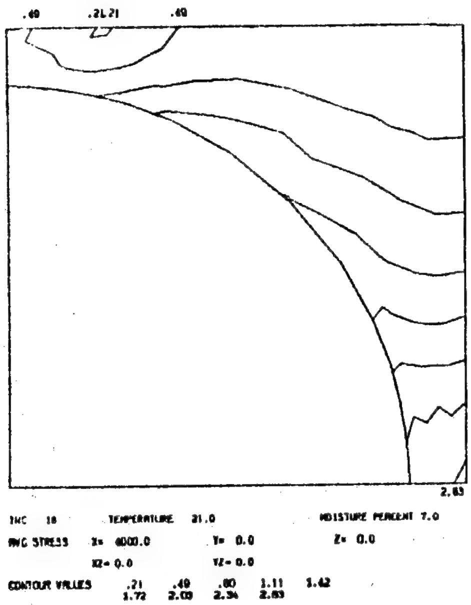


c) Interface Normal Stress (psi)

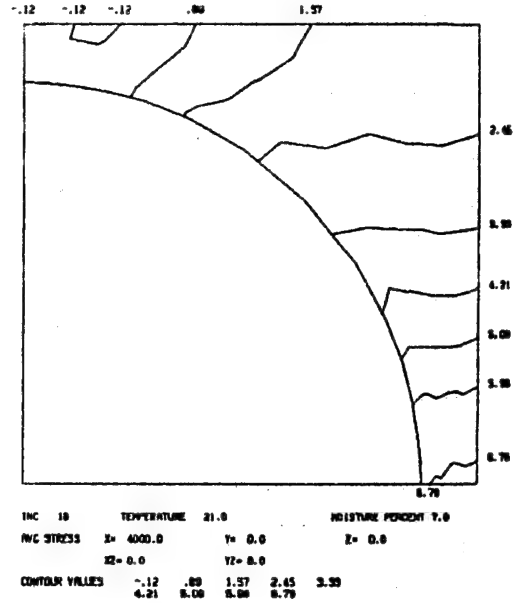


d) Interface Shear Stress (psi)

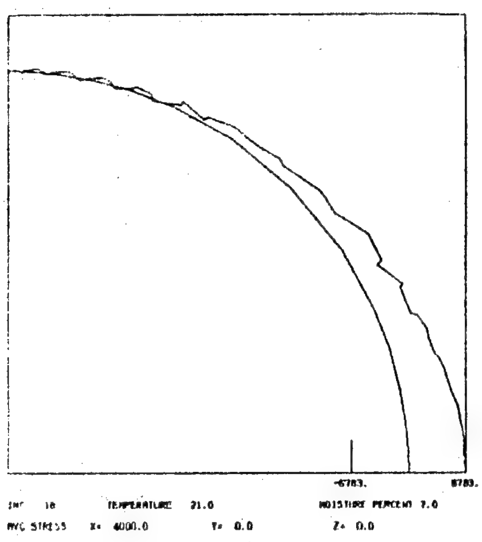
Figure E49. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, Dry (ETD); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



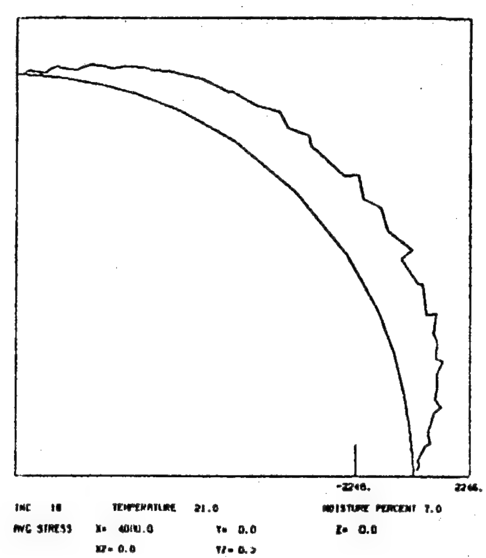
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

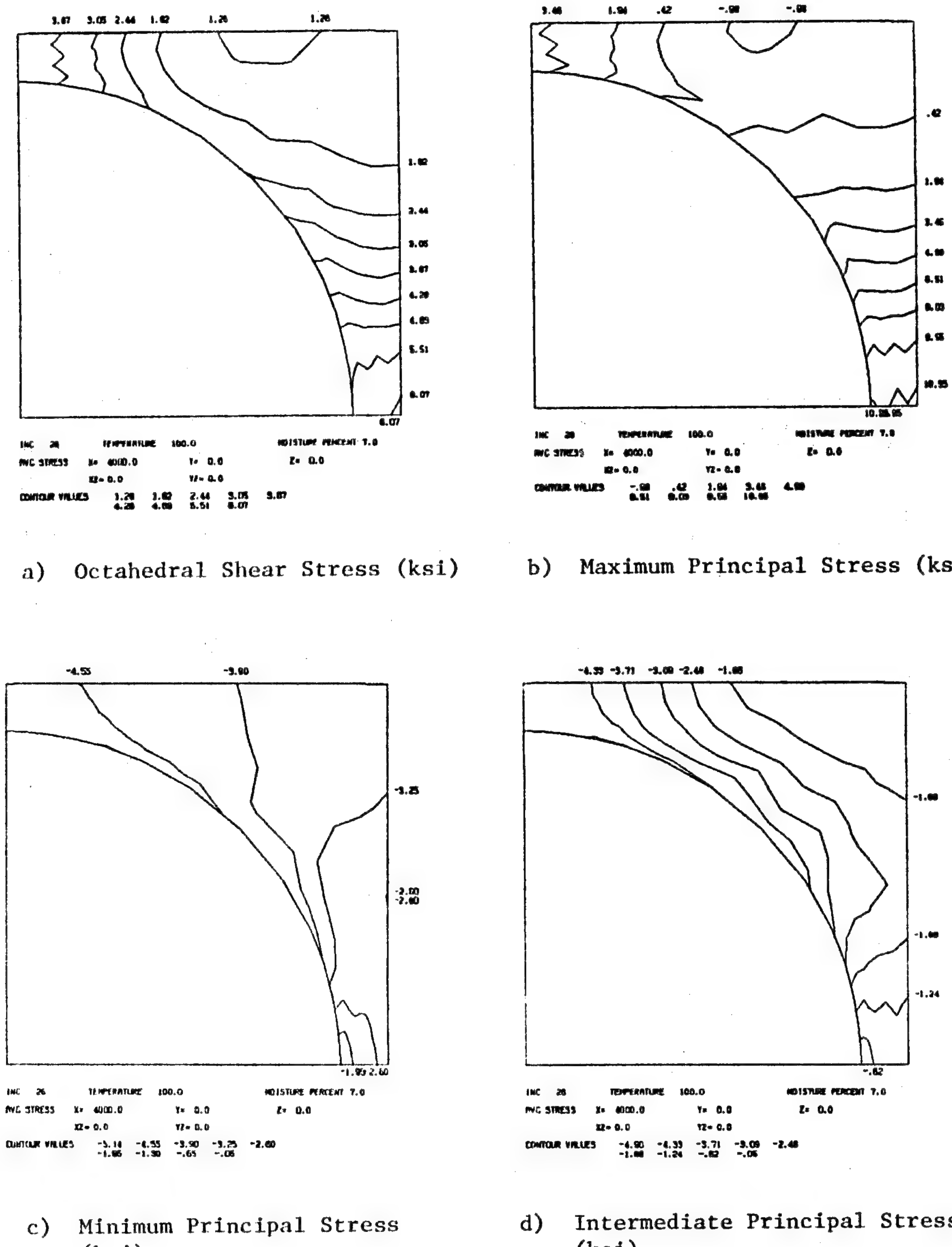


c) Interface Normal Stress (psi)



d) Interface Shear Stress (psi)

Figure E50. AS4/914 Graphite/Epoxy Unidirectionas Composite, Room Temperature, 7.0 Percent Moisture (RTW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



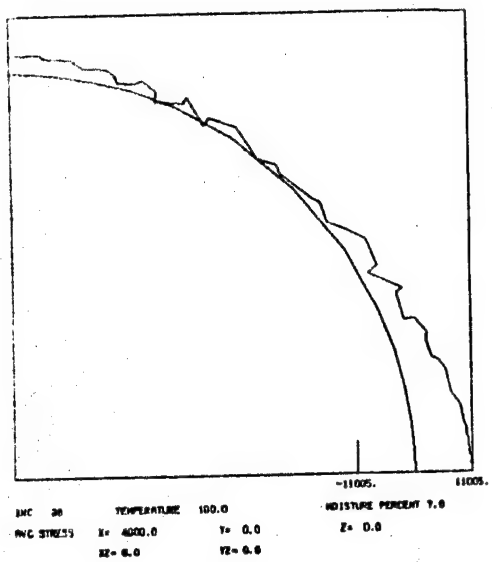
a) Octahedral Shear Stress (ksi)

b) Maximum Principal Stress (ksi)

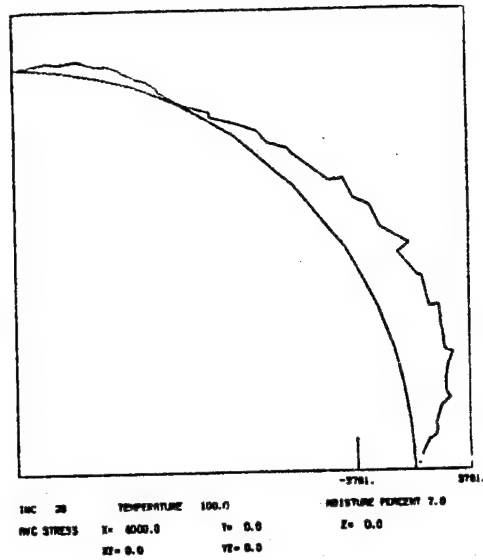
c) Minimum Principal Stress (ksi)

d) Intermediate Principal Stress (ksi)

Figure E51. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.

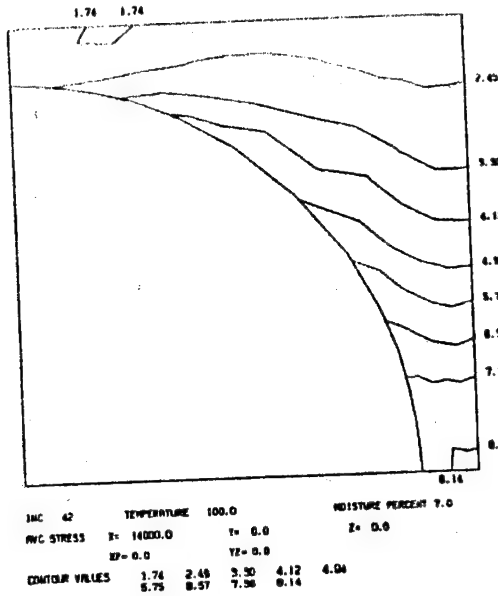


e) Interface Normal Stress (psi)

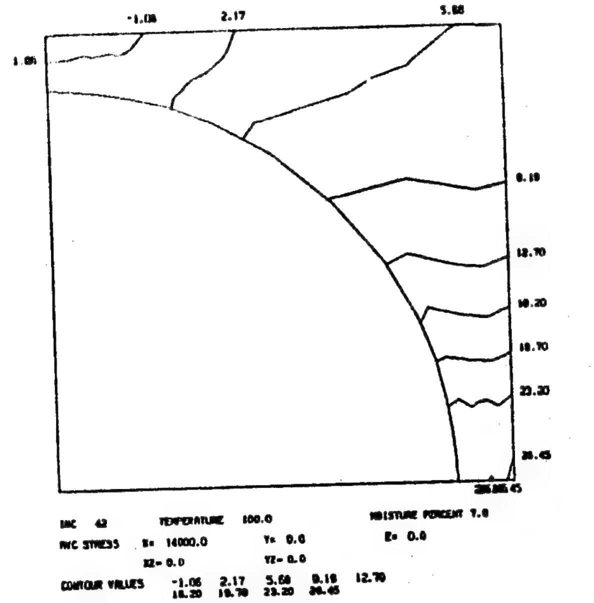


f) Interface Shear Stress (psi)

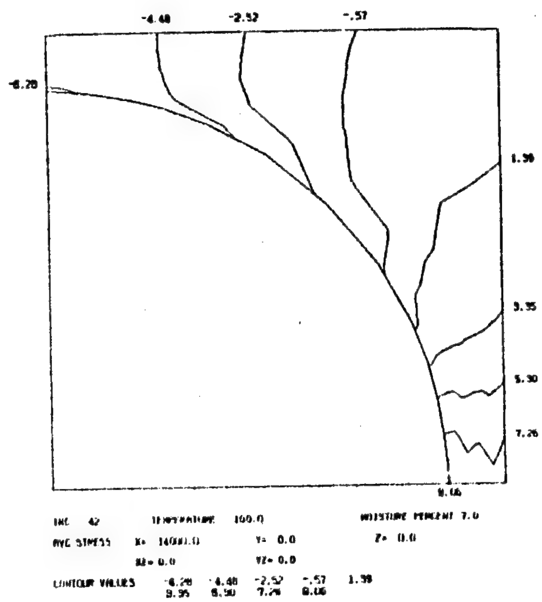
Figure E51 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 27.6 MPa (4 ksi) Transverse Tensile Applied Stress.



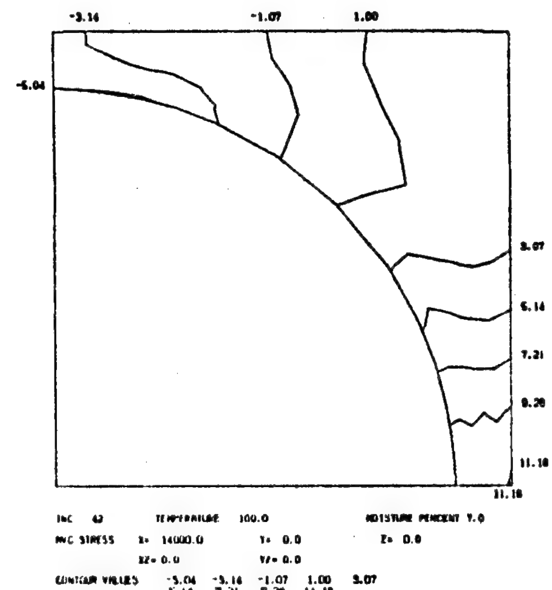
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

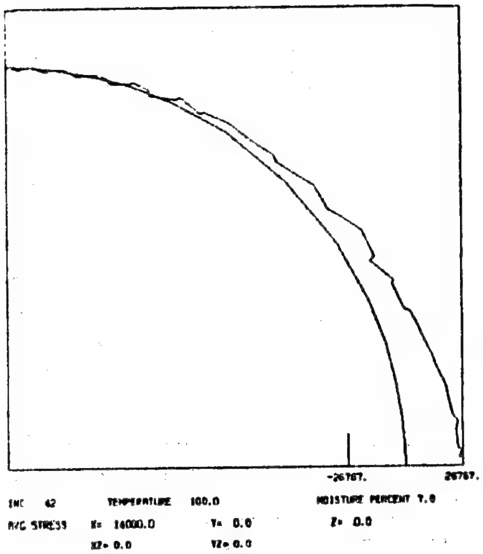


c) Minimum Principal Stress (ksi)

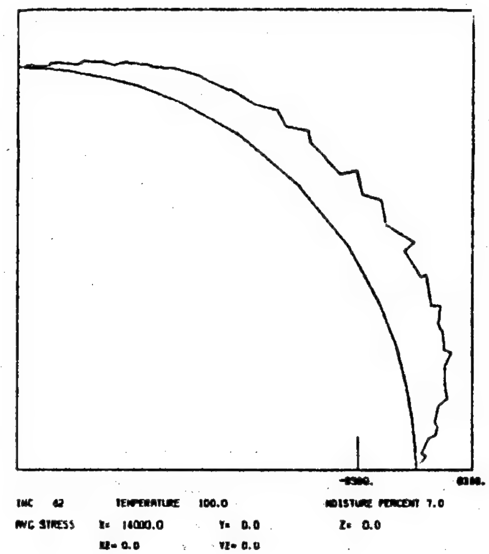


d) Intermediate Principal Stress (ksi)

Figure E52. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.

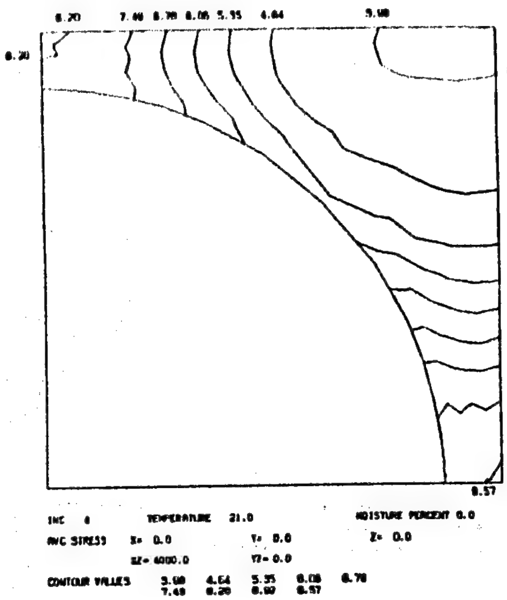


e) Interface Normal Stress (psi)

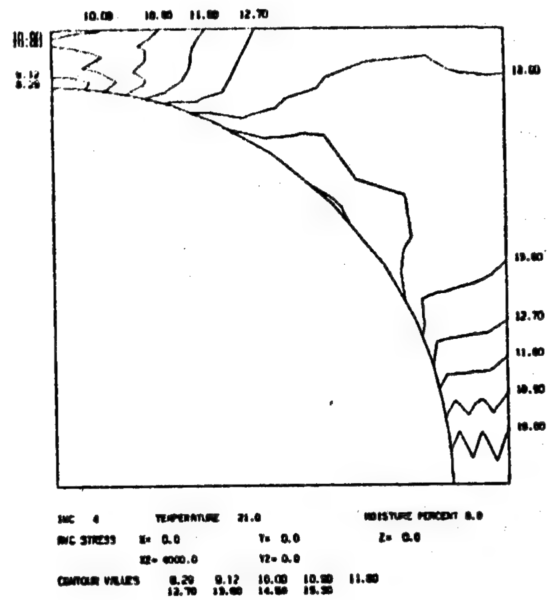


f) Interface Shear Stress (psi)

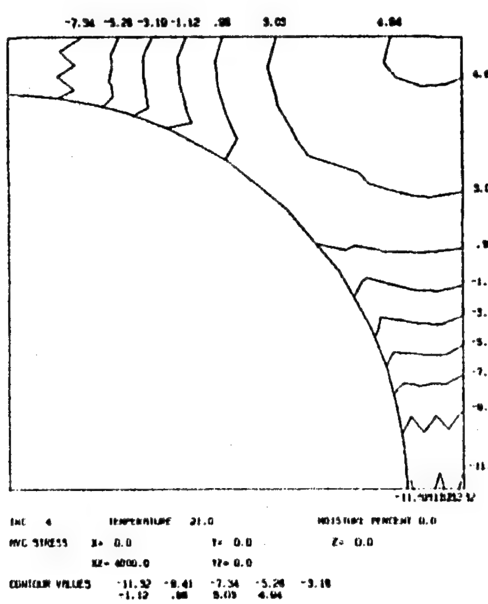
Figure E52 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 97 MPa (14 ksi) Transverse Tensile Applied Stress.



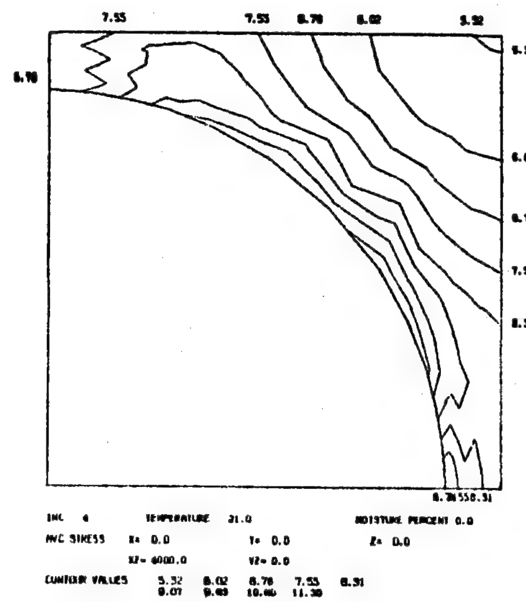
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

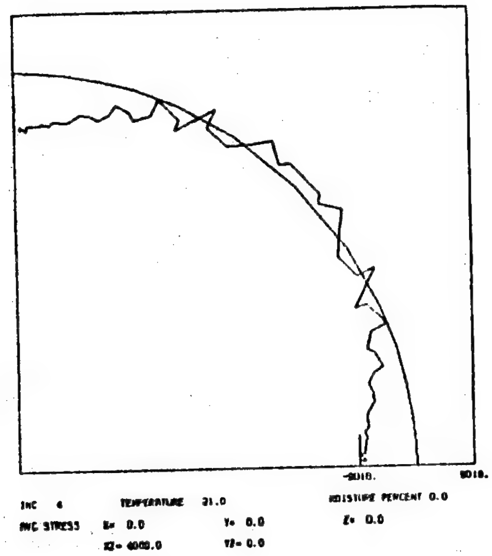


c) Minimum Principal Stress (ksi)

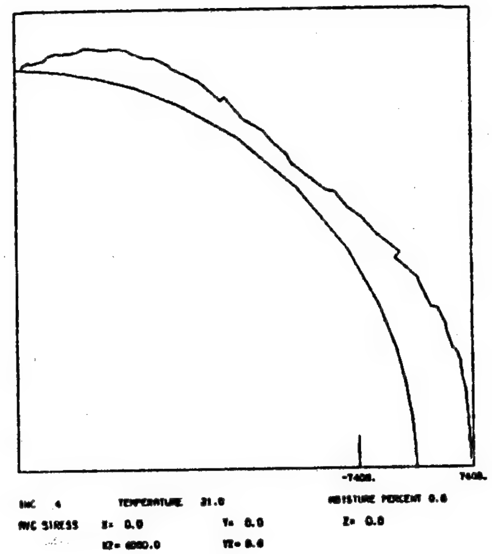


d) Intermediate Principal Stress (ksi)

Figure E53. AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.6 MPa (4 ksi) Longitudinal Shear Applied Stress.

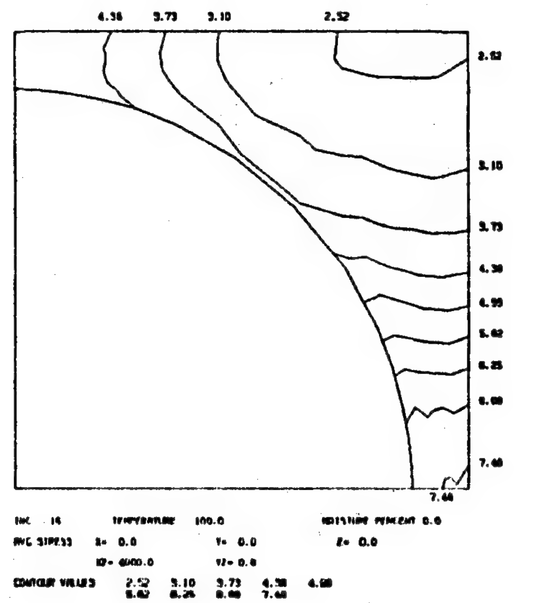


e) Interface Normal Stress (psi)

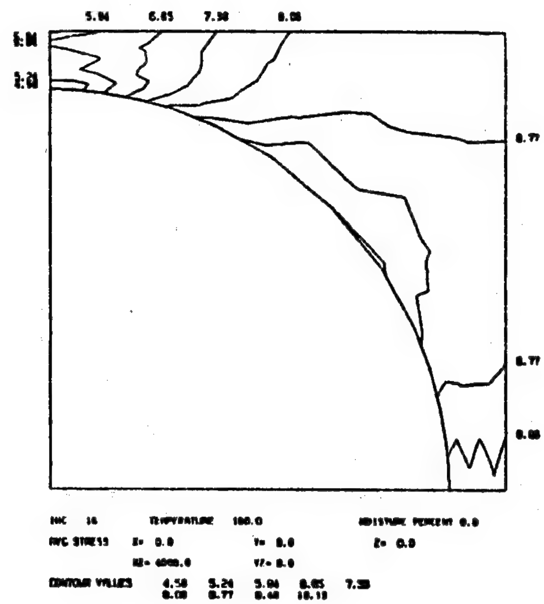


f) Interface Shear Stress (psi)

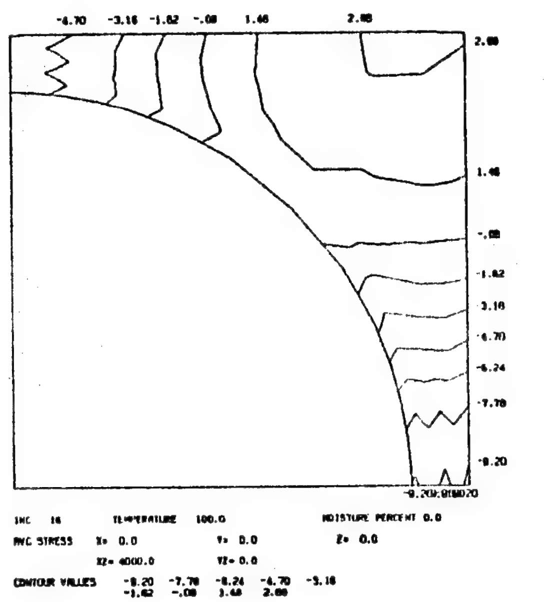
Figure E53 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, Room Temperature, Dry (RTD); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



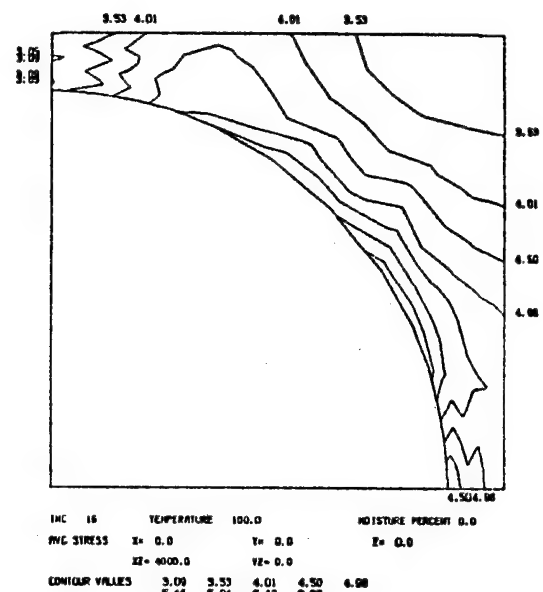
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

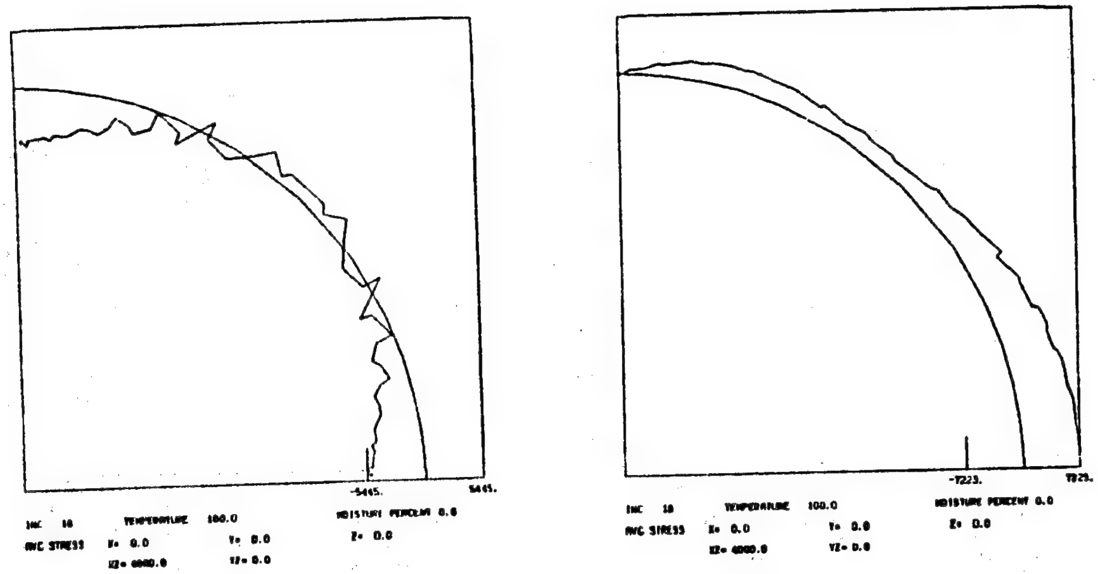


c) Minimum Principal Stress (ksi)



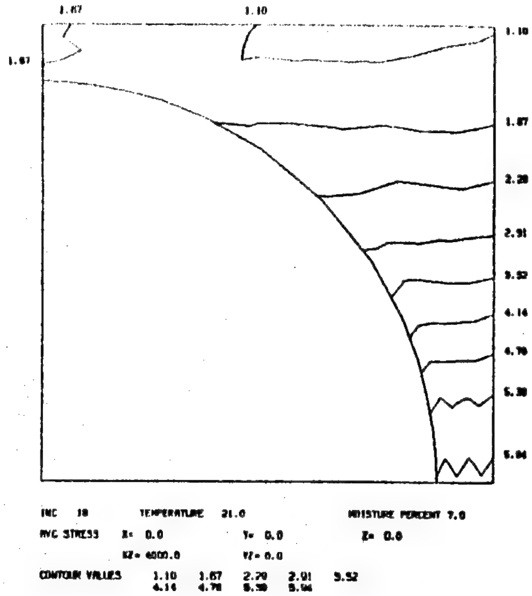
d) Intermediate Principal Stress (ksi)

Figure E54. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C Dry (ETD); 27.4 MPa (4 ksi), Longitudinal Shear Applied Stress.

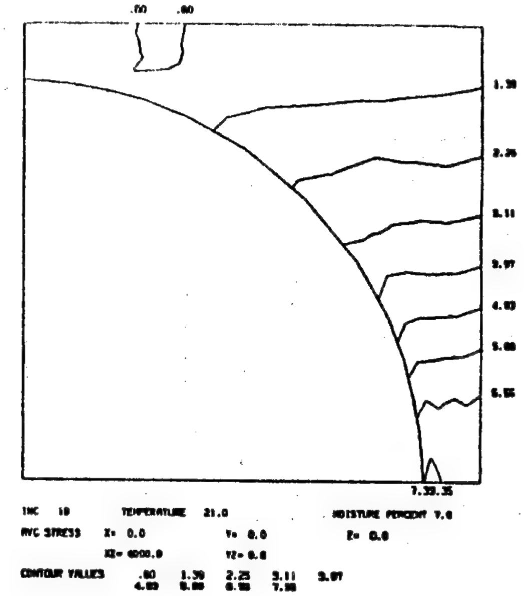


e) Interface Normal Stress (psi) f) Interface Shear Stress (psi)

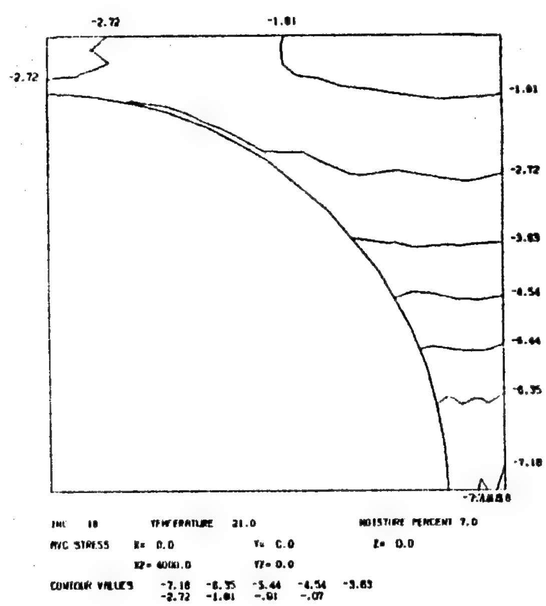
Figure E54 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 3.8 Percent Moisture; 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



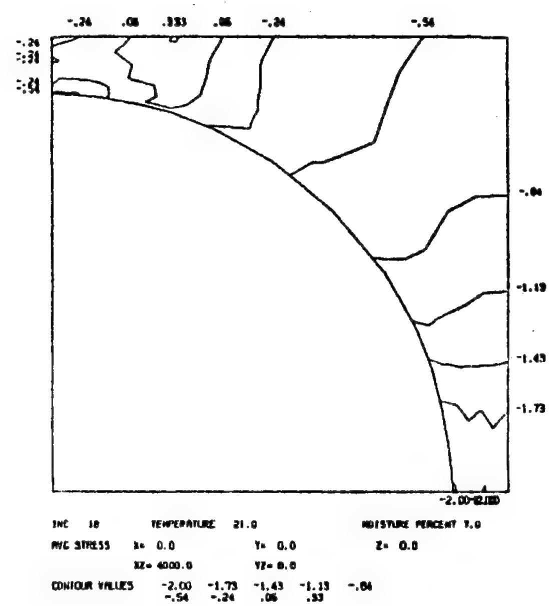
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

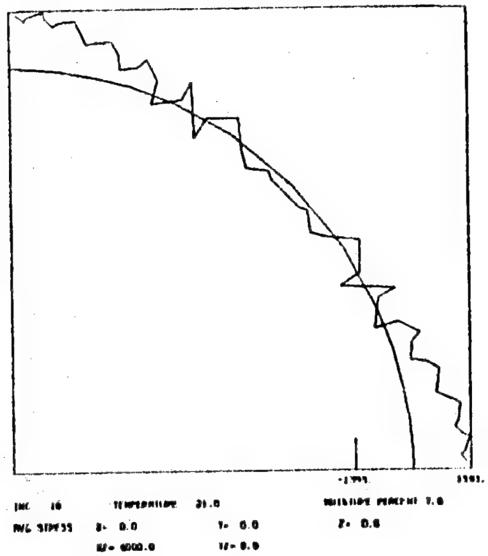


c) Minimum Principal Stress (ksi)

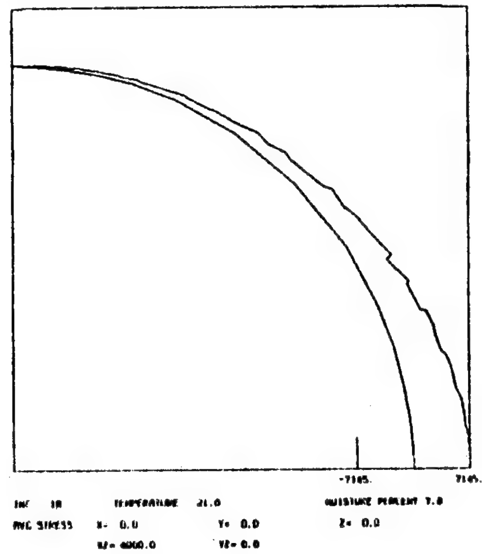


d) Intermediate Principal Stress (ksi)

Figure E55. AS4/914 Graphite/Epoxy Unidirectional Composite, 21°C, 7.0 Percent Moisture (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

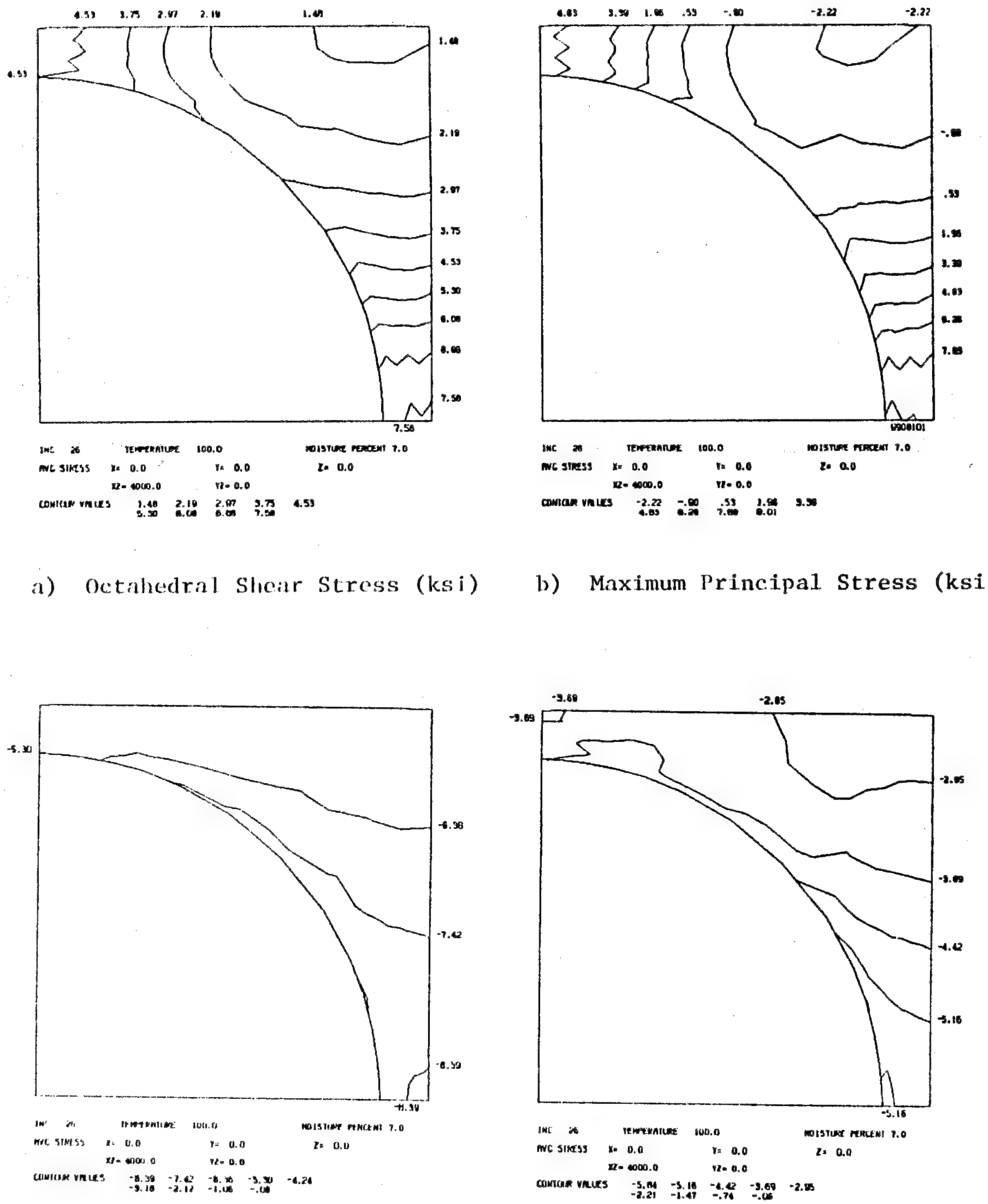


e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

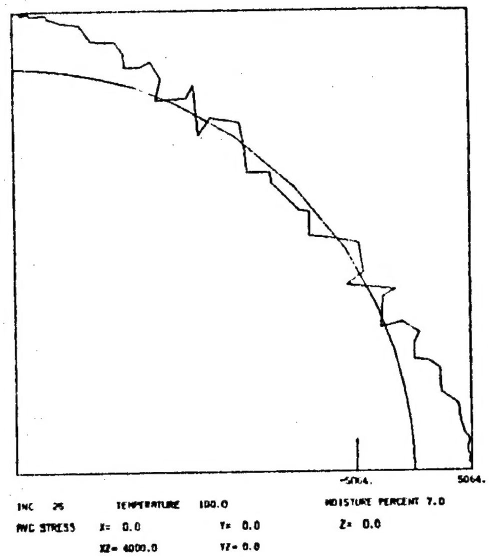
Figure E55 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 21°C, 7.0 Percent Moisture (RTW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



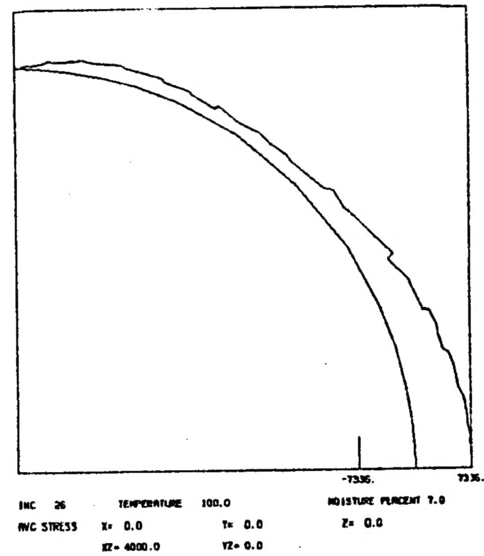
a) Octahedral Shear Stress (ksi) b) Maximum Principal Stress (ksi)

c) Minimum Principal Stress (ksi) d) Intermediate Principal Stress (ksi)

Figure E56. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.

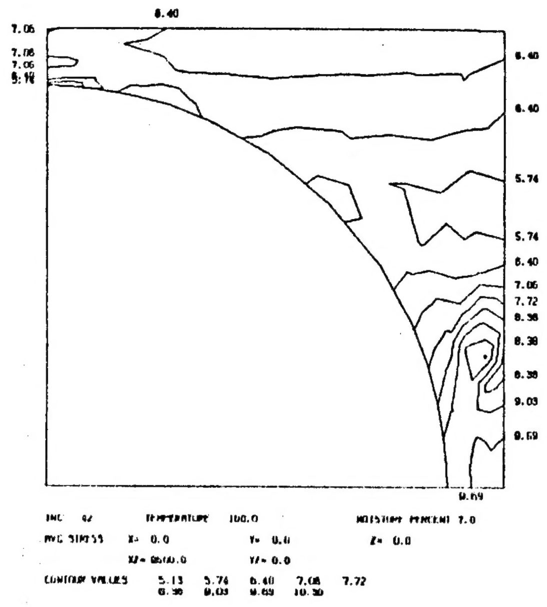


e) Interface Normal Stress (psi)

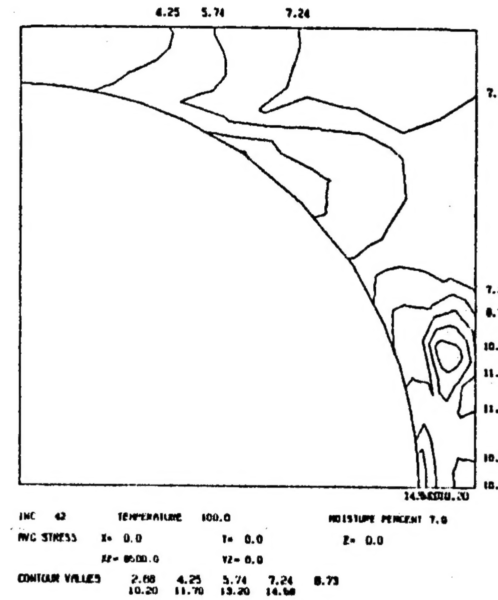


f) Interface Shear Stress (psi)

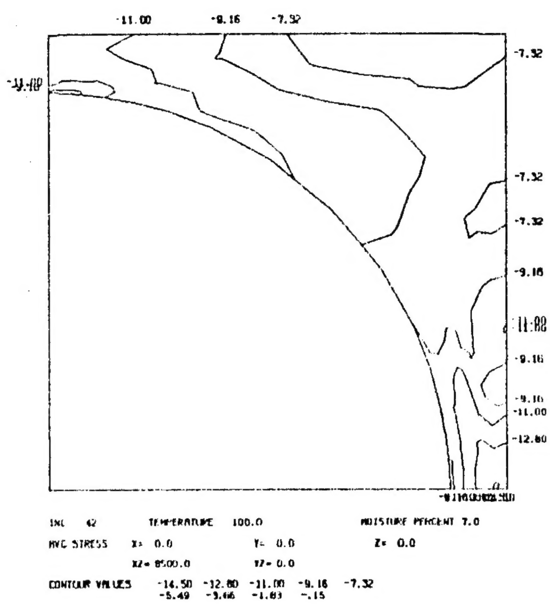
Figure E56 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 27.4 MPa (4 ksi) Longitudinal Shear Applied Stress.



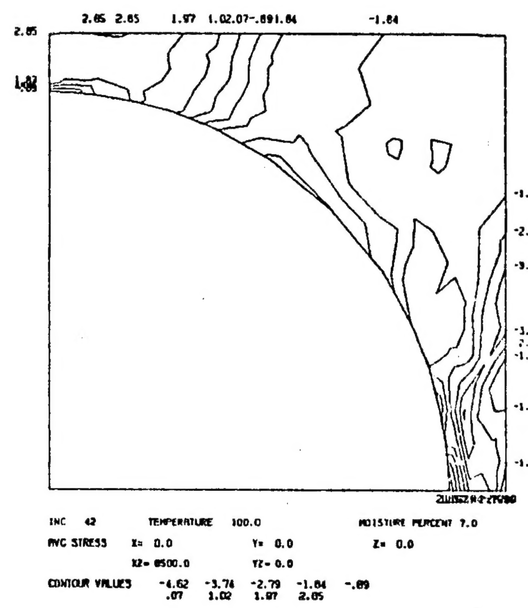
a) Octahedral Shear Stress (ksi)



b) Maximum Principal Stress (ksi)

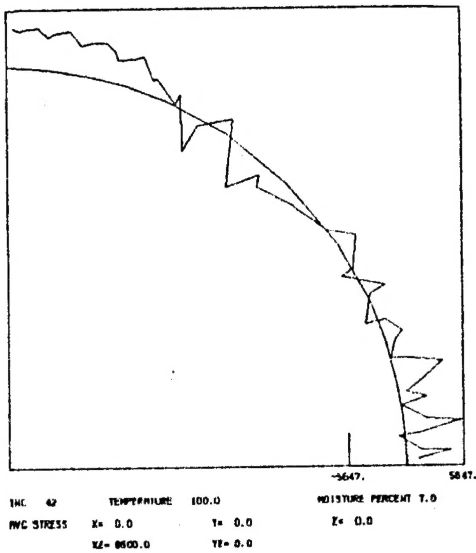


c) Minimum Principal Stress (ksi)

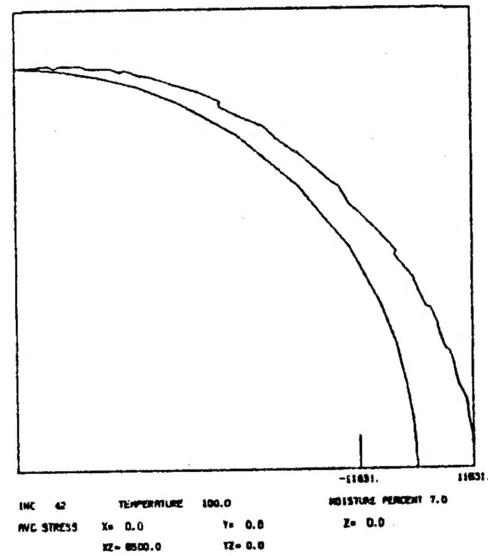


d) Intermediate Principal Stress (ksi)

Figure E57. AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.



e) Interface Normal Stress (psi)



f) Interface Shear Stress (psi)

Figure E57 (continued). AS4/914 Graphite/Epoxy Unidirectional Composite, 100°C, 7.0 Percent Moisture (ETW); 97 MPa (14 ksi) Longitudinal Shear Applied Stress.

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15. Supplementary Notes

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16. Abstract

A detailed evaluation of one untoughened epoxy baseline resin and three toughened epoxy resin systems was performed. The Hercules 3502, 2220-1, and 2220-3, and Ciba-Geigy Fibredux 914 resin systems were supplied in the uncured state by NASA-Langley and cast into thin flat specimens and round dogbone specimens. Tensile and torsional shear measurements were performed at three temperatures and two moisture conditions. Coefficients of thermal expansion and moisture expansion were also measured.

Extensive scanning electron microscopic examination of fracture surfaces was performed, to permit the correlation of observed failure modes with the environmental conditions under which the various specimens were tested.

A micromechanics analysis was used to predict the unidirectional composite response under the various test conditions, using the neat resin experimental results as the required input data.

The mechanical and physical test results, the scanning electron microscope observations, and the analytical predictions were then correlated.

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